Designing Open-ended Learning Environments to Foster Diverse Forms of Collaboration

By Vishesh Kumar

A dissertation submitted in partial fulfilment of

the requirements for the degree of

Doctor of Philosophy

(Curriculum & Instruction)

At the

University of Wisconsin—Madison,

2021

Date of final oral examination: 04 / 23 / 2021

This dissertation is approved by the following members of the Dissertation Committee:

Matthew Berland, Associate Professor, Curriculum & Instruction, UW–Madison

Erica Halverson, Professor, Curriculum & Instruction, UW–Madison

Mitch Nathan, Professor, Educational Pscyhology, UW–Madison

Mike Tissenbaum, Assistant Professor, Curriculum & Instruction, University of Illinois Urbana-Champaign

Peter Wardrip, Assistant Professor, Curriculum & Instruction, UW–Madison

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Chapter 1: Introduction

In this dissertation, I investigate and discuss the implications of specific design patterns in enabling different forms of collaborative behaviors in open ended learning environments. Through the use of qualitative analyses across three studies, these findings are aimed to help inform how to design learning environments that foster and support such diverse forms of collaboration. Understanding collaboration is a critical need since it has been long recognized as a valuable skill to learn (Trilling & Fadel, 2009), a productive process in supporting learning (Roschelle, 1992; Barron, 2000), and a learning outcome itself, most notably in the form of enculturation (Rogoff, Matusov, & White, 1996; Lave, 1991). Working to complicate and expand what is recognized and supported as useful collaboration is key in supporting more diverse forms of learning, learner preferences, and pluralities of engagement with learning, which in turn is a fundamental way to respond to calls of equity in the fundamentals of our work as learning scientists (Uttamchandani, 2018). Thus, I will answer how to design game-based learning environments to support different forms of collaborations, and how we can identify richer varieties of collaborative play in such environments using gameplay data from video, interviews, and game logs.

Dillenbourg (1999) describes collaborative learning scenarios as situations in which a group of learners are engaged in learning in ways that involve interacting with each other. Beginning with this broad frame of collaboration, we know that learners collaborate with each other in a multitude of ways, affected by their preferences, and the designs and needs of the learning scenario (Fan, et al, 2014).

We know from work on collaborative problem solving that engaging in certain forms of collaboration like sustaining a shared understanding of team progress on a problem (Barron, 2003) supports greater success in joint tasks. Recent work in more open-ended learning environments (Tissenbaum, Berland, & Lyons, 2017; Halverson, Gravel, & Litts, 2018) show how rich learning still takes place without sustained coordination, especially when notions of success are broadened to include different kinds of individual and collective progress. This pushes us to more deeply consider the emergent and divergent ways learners collaborate in spaces where they are provided increased flexibility and agency in choosing to engage towards self-directed goals and interests.

These expanded considerations are especially relevant since not all learners prefer to engage socially and collaboratively in similar ways. Although well-coordinated groups can manage complex tasks that individuals would not be able to do (Hutchins, 2000), group work can also lead to individuals performing worse than their individual competencies support (Barron, 2003). This is often a result of the provided task and group configuration not working in those learners' favor (Van den Bossche, et al, 2006). This provides a clear need to design learning scenarios where participants can collaborate in more flexible ways suited to various needs and preferences. Rather than forcing learners to learn specific forms of collaboration well suited to a narrow set of tasks, they should be provided with access to a variety of open-ended collaborative learning scenarios, which presents more valuable spaces to develop and practice personally relevant ways of collaboration and social engagement for learners. This is coupled with a need to be better equipped to also recognize these different forms of collaborations, and the understandings that learners can gain through engaging with them.

Thus, in this thesis I present my work across three different technology-enhanced collaborative learning environments. The design of these environments and how they appropriately serve the questions of interest are explained in the methods section.

- **Connected Spaces** – an ambient interface intended to bridge help seeking and help giving opportunities among peers in a project-based learning environment;
- **Rainbow Agents** – a collaborative computational gardening game which supports placing and programming gardening agents through two touchscreen controllers on a shared garden; and
- **City Settlers** – a multi team, location based in-room city management simulation, where teams of participants work to develop their cities while balancing economic, ecological, and social constraints.

I use these environments as exemplifying designs which support a wide range of collaborative engagement, to answer the following research questions:

1. Using mixed methods analyses of gameplay in these environments, how do we identify learners engaging in different forms of collaboration/social learning? As explained in further sections, this is operationalized as developing understandings about the system, choosing goals and roles relative to each other (competitors, mentees, collaborators, etc.), and negotiating these goals and roles over time
    a. What aspects of the scenario's design support certain engagements to happen more than others?

This thesis aims to help educational researchers in analyzing learner experiences in a variety of learning environments. By describing how to identify different forms of collaboration in classrooms as well as museum spaces in a variety of social configurations, researchers are better equipped to recognize a broader set of interactions as productive forms of learning. Understanding the role of design in supporting such ranges of collaborations aims to guide learning designers, scientists, and researchers, in creating and modifying spaces to support forms of collaboration particularly productive for their chosen goals. Adoption and expansion of such perspectives can enrich analysis, design, as well as facilitation practices.

1.1. COLLABORATION AS A PHENOMENON

Here I delve into prior work on describing collaborative interactions. The primary components categorizing social interactions of interest to this work are grouped under goal orientation, roles, and negotiation. The studies through my thesis focus on investigating these components to different levels of detail.

1.1.1 Collaborative Goals

In this section I both demarcate my usage of the different and often overlapping terms – collaboration, cooperation, coordination, and competition – and use pre-existing frameworks to focus on the different kinds of goal 'orientations' these different forms of participation entail. By goal orientation, I refer to how the goals of participants are related to each other, explained as follows.

Dillenbourg (1999), and Johnson & Johnson (1996) demarcate cooperation and collaboration to be different focuses on learners working together – cooperation involves "working together, but separately", and collaboration is "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" (quoting Roschelle & Teasley, 1995).

In this work, I use the term *coordination* to refer to what Roschelle and Dillenbourg demarcate as the scope of collaboration, i.e., when learners maintain (positively) *coordinated* shared goals. I use *cooperation* to match their conception of learners dividing work across each other and working in parallel without requiring sustained coordination. I call these forms of engagement different kinds of collaboration since these environments are broadly called collaborative learning environments. I use the terms collaboration, social configurations, and similar phrases interchangeably.

In contrast to these goal orientations which are often described as positive interdependence – wherein learners' actions positively contribute – another common form of collaboration (/social configuration) is competition. Defined as a scenario where participants' success is mutually exclusive, competition is typically an individualized pursuit, often found to be less beneficial than "collaborative" participation where participants share goals and coordinate their pursuits (Peppler, Danish & Phelps, 2013). When compared on the same task, or richness of communication generated, individual competition is often found to be impoverished compared to coordinated activities. Competition has been found to sometimes worsen performance (Johnson, Johnson, & Stanne, 1986), but sometimes increase engagement as well as performance (Cagiltay, et al, 2015).

These notions of competition often overlook the dynamic of actively strategizing against each other participants, particularly in response to their actions found in strategic games which involve rich, complex thinking (Berland & Lee, 2011). Learning to strategize in team sports is a prominent example of where teams work in complex manners against other teams and creates space for rich forms and methods of learning (Gréhaigne, Godbout, & Bouthier, 2001).

These goal orientations make up different kinds of collaborations (/collaborative interactions) – competition, parallel, cooperative, and coordinated – vary in how much the local (and global) goals of the participants are *aligned*/shared, and how actively their actions are coordinated or *interacting* with each other (Figure 1).

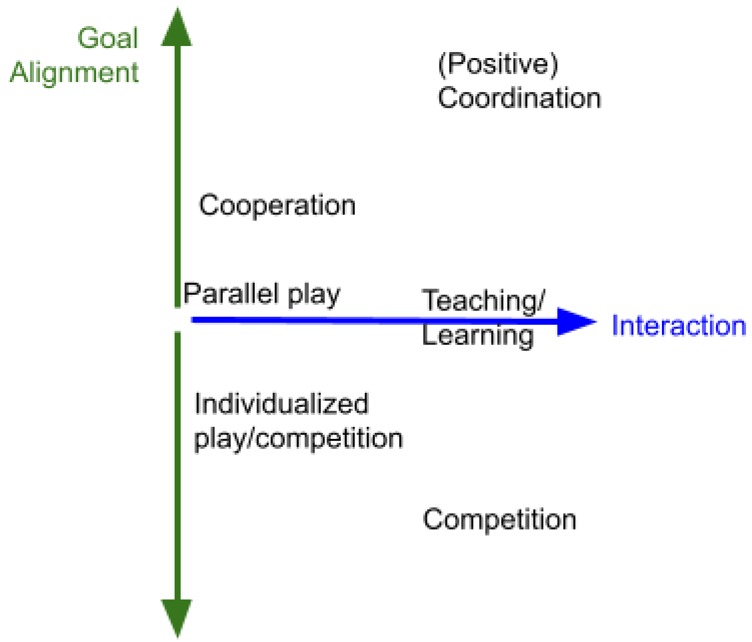


Figure 1. Listing different social configurations (in learning environments) along the axes of Goal Alignment and constancy of Interactions.

Competition: In this mode, participants pay attention to each other's actions, and actively strategize against others.

Individualized/Parallel: Here, participants don't directly interact with the other participants' actions, and is most often found in classrooms, but also in many open-ended learning environments. Competition in classrooms is individualized in this form (Johnson & Johnson, 1999) – sometimes student performance is unrelated to others (grading by thresholds) and sometimes it affects others' results (grading on a curve). Museum exhibits with multiple controllers often see parallel un-coordinated play (Inkpen, et al., 1999).

Cooperation: Similar to parallel play, cooperation is when participant actions involve working on "separate" tasks but are positively interdependent on each other and act with a greater coordination about the overall goal. For instance, jigsaw activities (Aronson, 1997) where subgroups work on different sections of a project, and synthesize their separate works at the end, is a recognizable form of cooperative participation.

Coordination: Closest to Roschelle & Teasley's notion of collaboration (1995), coordination refers to scenarios where participants are working on a shared goal, and actively coordinating their actions to make progress towards the shared task. This is most recognizably seen in work on collaborative problem solving (Barron, 2000; Roschelle & Teasley, 1995), and also the interactions of greatest interest in research on community level learning (Rogoff, Matusov, & White, 1996; Lave, 1991).

As hinted at but inadequately depicted in Figure 1, interpersonal dynamics like teaching-learning are high in "interactivity", but don't belong to a specific goal orientation (they take place in competitive as well as coordinated scenarios). This is further discussed in the other components of collaborations.

1.1.2. Collaboration Roles

Orthogonal to goal orientation (i.e., occurring in conjunction with and complimenting) goal orientations, collaborative interactions entail a relative role taking between participants. This is operationalized at varying levels of details across different frameworks aimed at describing collaborations.

Dillenbourg (1999) categorizes collaborative interactions as comprising of the following three aspects:

- **Interactiveness** – Collaborative interactions should involve some [agentic] participation by the participants being considered. Conducted actions receiving a response, ideally from another participant in an agentic or non-trivial manner, is critical in being able to call an interaction collaborative. The degree of interactivity – either at planned time periods, or constant negotiation – would make for different kinds of collaborative interactions.
- **[Synchronous] Communication** – The extent to which the collaborators are synchronous in their communication, makes for different kinds of collaborations. Sometimes, a meta-synchronicity contract enables continued collaboration – posting work to a forum, or in ways that is expected to receive a response and building upon by other collaborators – provides for sustained collaboration despite an asynchronicity in the communication.
- **Negotiability** – Dillenbourg describes multiple kinds of negotiations. Negotiation occurs around activities in the setting which are negotiable.
    - If the roles and sub tasks are not a priori demarcated, there is space for negotiation around who will do what – a *role-based or meta-task negotiation*.

- Then, there is *goal-based negotiation* which involves developing a shared conception of the overall goal and underlying activities. This comes up in the conception of collaboration which requires a constantly shared understanding of the activity's goal.
- Finally, there is *conceptual negotiation* which involves participants engaging with each other's understanding of concepts. Concepts here, would typically refer to the mechanics underlying the practice that the participants are engaging in, which may not always be distinguishable from role-based or goal-based negotiation.

Barron's (2000; 2003) categorization of the interactions taking place in a collaborative problem-solving activity, provides a detailed look into different kinds of *synchronicity* with which communication occurs:

- **Parallel interactions** were characterized by exchanges of comments about the task with few attempts to monitor the other person or to share thinking.
- **Associative interactions** were those in which children tried to share information about a task, but no attempt was made to coordinate roles.
- **Cooperative interactions** were those in which children constantly

monitored each other’s work and played complementary roles in completing the problems – “One child may perform an observing, guiding, and correcting role while the other performs task procedures” (p. 341)

Barron (2000) further breaks down the kinds of talk that take place during cooperative interactions:

- share knowledge
- share processes of monitoring solutions
- **explain one’s thinking**
- **observe peers’ strategies**
- **provide critique**, and
- **engage in productive argumentation**

The bolded categories add on earlier and broader schemes by delving deeper into conceptual negotiations and expanding the focus from goal-based negotiations.

Tissenbaum, Berland, & Lyons (2017) extend Barron’s, Roschelle’s, and Fleck’s work on convergent conceptual change, to study open-ended learning environments like museum exhibits. When participants do not have prescribed aligned goals, they collaborate in more flexible manners which provide different advantages to the participants. They describe verbal and gestural communication among participants as such:

1. Mechanisms of collaborative discussion

a. Making and accepting suggestions

b. Clarification

c. Negotiating

d. Seeking help

2. Mechanisms for enacting divergent collaboration

a. Joint attention and awareness

b. Goal adaptation

c. Boundary spanning actions

d. Boundary spanning perception

e. Narrations

f. Modeling

In the studies across this thesis, I use a combination of these models to present detailed cases around the different kinds of collaborative interactions that emerge and take place. In the collated discussion at the end, I fold in most of these different categories under the two broad frames – role-taking, and negotiation. Engaging as a learner, teacher, *appropriator* of ideas, domineering driver, and others are different kinds of roles learners adopt with each other – in all kinds of learning environments, not just open-ended ones. A key goal of this thesis is to expand our understanding of how to design environments to foster roles valuable to different learning experiences.

1.1.3. Negotiation

As mentioned in Dillenbourg's description of collaborative interactions, and reoccurring across the other frameworks in different forms, negotiation is often a key "axis" which makes an interaction appear to be more *involved* or active. It is described as "productive argumentation" in Barron's descriptive qualities and reoccurs in Fleck's and Tissenbaum et al.'s work as Negotiating, as well as in Goal Adaptation.

In this work, negotiation is of particular interest when it is tied to an evolution of learners' goal orientation and social roles relative to each other (thus overlapping with the *goal adaptation* category). Negotiation also occurs when learners exchange understandings about the relevant learning domain, especially when it is different across the learners and leads to mutual growth. Even the realization of differences, without conclusive convergence of conceptual change, acts as avenues for learners to seek and develop understandings divergently.

1.2. DESIGNING FOR COLLABORATION

In this section, I discuss the different ways designing learning environments has been discussed across literature, in particular learning sciences and learning design work related to collaborative learning.

Dillenbourg (1999) highlights the following elements as guiding the nature of collaborative interactions taking place in a learning environment, and as a framework for designing for collaborative learning:

- **Setup of initial conditions**: Creating an environment, in terms of available tools, and especially diversity among participants (of expertises, knowledge, viewpoints, interests), increases the salience of the value of collaborative interactions among participants.
- **Role-based scenario**: Presenting complex tasks which require multiple kinds of knowledge to accomplish are often more likely to foster collaborative interactions.
- **Interaction rules**: Setting up rules for how to engage in the environment or participate in the prescribed activity can afford for certain forms of collaborative interactions to take place. At the same time, not prescribing disjoint roles supports different forms of engagement and growth and is better suited for certain environments (Baker & Lund, 1997).
- **Monitoring and regulation of interactions**: "Productive" collaboration (typically with respect to successful completion of tasks, or sustained engagement from participants), is substantially helped when the environment has tools and supports for knowing the status and consequences of different actions happening in the environment. This can take the form of interfaces which present information collective progress,

group behaviors, etc., either to support participant awareness, or to keep facilitators informed in ways they can meaningfully intervene and support richer participation.

Non-verbal forms of collaboration and flowing between active and passive engagements with other participants' actions, are uniquely supported in **face-to-face** learning environments (Lui & Slotta, 2014). The movement of knowledge and understandings is also uniquely supported through co-presence. When participants are free to pursue a variety of goals and tasks but share a common orientation, "collaboration through the air" (Halverson, Litts, & Gravel, 2018; Kafai & Harel, 1991) takes place wherein awareness of others' work and exchange of ideas among participants enables the synthesis of novel ideas that is much harder in long-distance, online, or asynchronous environments. The lack of non-verbal cues and tonality in the lack of face-to-face copresence also leads to poorer interpersonal engagements and group trust, leaving participants dissatisfied with group participation (Ocker & Yaverbaum, 1999).

As a result, my work is primarily focused on environments where people are physically co-located – addressing Dillenbourg's category of supporting richer monitoring and regulation of participant interactions.

The work on emergent and scripted roles (Strijbos & Weinberger, 2010) deals with Dillenbourg's category of **role-based scenarios**. In environments with scripted roles, participants engage in different sections of a given task, intended to help them learn specific things. The differentiated learning across roles is typically balanced by rotating roles, so that each participant accesses the different opportunities for learning. These activities, like jigsaw learning activities, are often cooperative across groups, and are limited in flexibility of participation.

Work in emergent roles studies the kinds of flexible role choices I am interested in through the environments being analyzed in this thesis. These are best fostered by engaging participants in a **complex task** which is not easily done individually, and with interdependent components that require coordination for continued successful usage (Fan, et al, 2014). This is instantiated in Antle et al.'s YouTopia (2013), which plays a strong inspirational role in the design of the games being studied.

In this work, I extend these guidelines for designing activities to support a rich variety of collaborations, along with markers on the relationships between certain affordances and the collaborations they support.

Through the following studies, I present examples of how to identify these different forms of collaboration. These analytic methods include coding schemes, descriptive frameworks, and data mining examples which encapsulate examples of collaborating in different forms. I also examine the role that specific design elements used across the projects played in enabling different kinds of social configurations and collaborative interactions.

Chapter 2: Ambient Representation Tools for Divergent Collaboration: Design-Based Research Using Actor Network Analysis

2.1. INTRODUCTION

Bereiter (2002) emphasized the value of enculturation into knowledge building communities as integral to preparing students to be competent members of the Knowledge Age. In practice, learning collaboratively has been seen to both broaden and deepen learning experienced by peers (Marttunen & Laurinen, 2007). Cho & Macarthur (2010) describe how working with peers tends to generate non-directive feedback which enables more complex analyses and repairs in understanding; Zhang et al. (2009) discuss the importance of collective responsibility among groups of students and also call for an increase in cross-group interactions. Giving students opportunities to mentor their peers helps them develop identities as authentic "experts" in a domain (DuBois & Karcher, 2013); this is particularly important for youth underrepresented in STEM (Maltese and Tai, 2010).

A key challenge in enabling cross-group collaborations lies in students having an awareness of their peers' different expertises (Ogata & Yano, 2000). At the same time, the provision of such awareness should not take away from students' attention to their work, or their sense of agency (Engle & Conant, 2002).

Ambient interfaces have been shown to be an effective and non-intrusive means of providing information (Ishii et al., 1998). Especially in learning environments like math classrooms, ambient representations have been successfully used to support help seeking and providing assistance (Alavi & Dillenbourg, 2012); however, this work focused entirely on supporting teachers to help students rather than viewing the whole class as a learning community.

Building on the above benefits of providing unobtrusive ambient support for peers to support one another when engaged in learner-driven inquiry activities, we developed Connected Spaces (CxS, Kumar, et al., 2017). CxS aims to support cross-group collaboration in environments like makerspaces and computing classrooms in which learners are developing their own solutions to self-identified problems, and in the process develop divergent, but potentially complementary skills (Tissenbaum, Berland, Lyons, 2017). CxS (Figure 1) is an ambient interface that allows students to see each other's skills and serves as a means to display students' requests for help in a persistent, but unobtrusive way.

To understand the effect a designed agent like CxS has on a classroom environment – comprising of teachers and students with pre-established roles – and its ability to change actor-relations to create a more collaborative learning community, we turned to Latour's Actor-Network Theory (ANT – Latour, 2005).

ANT is increasingly recognized as a valuable analytic framework for educational theory and practice (Fenwick & Edwards, 2010). ANT proposes considering environments as being composed of entities – humans and non-humans being treated equivalently – and the relationships which form between them. These relationships and entities change (*translate*) each other, and exist as a network in flux, allowing for unique insights into the kinds of actions, objects, and practices, which make a social environment function the way it does. This framework proposes regarding non-human entities as equivalently powerful and *agentic*, making it uniquely suited to studying the designs of tools in learning environments and the mechanisms through which they succeed or fail in rendering the kinds of social networks desired from [technological] interventions.

Thus, in this study we use ANT to conduct design-based research (DBR - Barab & Squire, 2004) around the abilities of CxS in making classrooms collaborative learning communities. Successful DBR relies on adjusting designs based on emergent realizations during their enactment (Hoadley, 2004). As such, ANT is a particularly useful lens for understanding a DBR implementation, as it allows the researcher to reveal the effects of a particular technological intervention within a complex social learning system, towards making necessary adjustments to the intervention to better support its intended pedagogical goals.

This work serves as an attempt to understand how CxS can support an entire class – teachers and students together – to work as a learning community, supporting each other as they engage in divergent forms of student-driven inquiry (Tissenbaum, Berland, & Lyons, 2017; Halverson, Litts, & Gravel, 2018). Through this work, we also aim to understand how an ANT approach can reveal the efficacy of a particular design-based research intervention during its live implementation. Three questions drove this research:

1. In what ways did the Connected Spaces platform support a classroom to act as a learning community while engaged in open-ended, learner-driven computing activities?
2. How did an Actor Network Theory approach help us understand how Connected Spaces was being used in the classroom?
    a. What were the different kinds of collaborative interactions participants engaged in, constituting these actor networks?
3. What changes were made to the design Connected Spaces as a result of the understanding revealed through Actor Network Theory throughout the study's enactment?

2.2. METHODS

2.2.1. Participants and Setting

This study took place in a large urban high school in northeastern United States, which has been recognized as one of the most ethnically diverse public high schools in the country. The curriculum was developed in close co-design with two teachers running engineering design and computing classes respectively in complement with each other. For the purposes of this study, we will only be looking at the last week of the computing class. This class involved twenty-four students from grades 9 - 12 (average age 15.8 years).

Co-researchers in the study developed a curriculum that contextualized the learning in an authentic context: students across classes worked together to develop solutions for cleaning up the local riverway. This was in the spirit of Tissenbaum et al.'s Computational Action (2019), which aims to position and support computing learners as becoming agentic actors in their communities, able to design and develop solutions that serve the needs of the community around them. The engineering class built the physical elements of the solution in a makerspace in the school, and the computing class (Figure 2) built apps that extended and augmented them. The class was held in the spring of 2018, for a half-semester duration of 8 weeks, where the first 5 weeks involved introduction and training around the development tools (App Inventor for the computing class as described in the next section), and design thinking practices to brainstorm and refine their project ideas. The last 3 weeks involved dedicated development time where the students were paired in groups and focused on making their group projects. This project work was done in pairs of students, where most of the pairs were made by the teacher, informed by student preferences. This assignment was done considering the diversity of the classroom across gender, race, prior knowledge, and also neurodiversity. We did not know the students to have experience from other formal computing education but had varying amounts of experience with tools like Scratch. There were five Black students, eight girls, and two students with specific neurodivergent needs who were paired with other students who had some experience and understanding of how to be productive team members for them.

Connected Spaces, the tool designed to support across group collaboration was introduced in the classroom during the last week, which is the period of focused data collection and highlighted in this study.

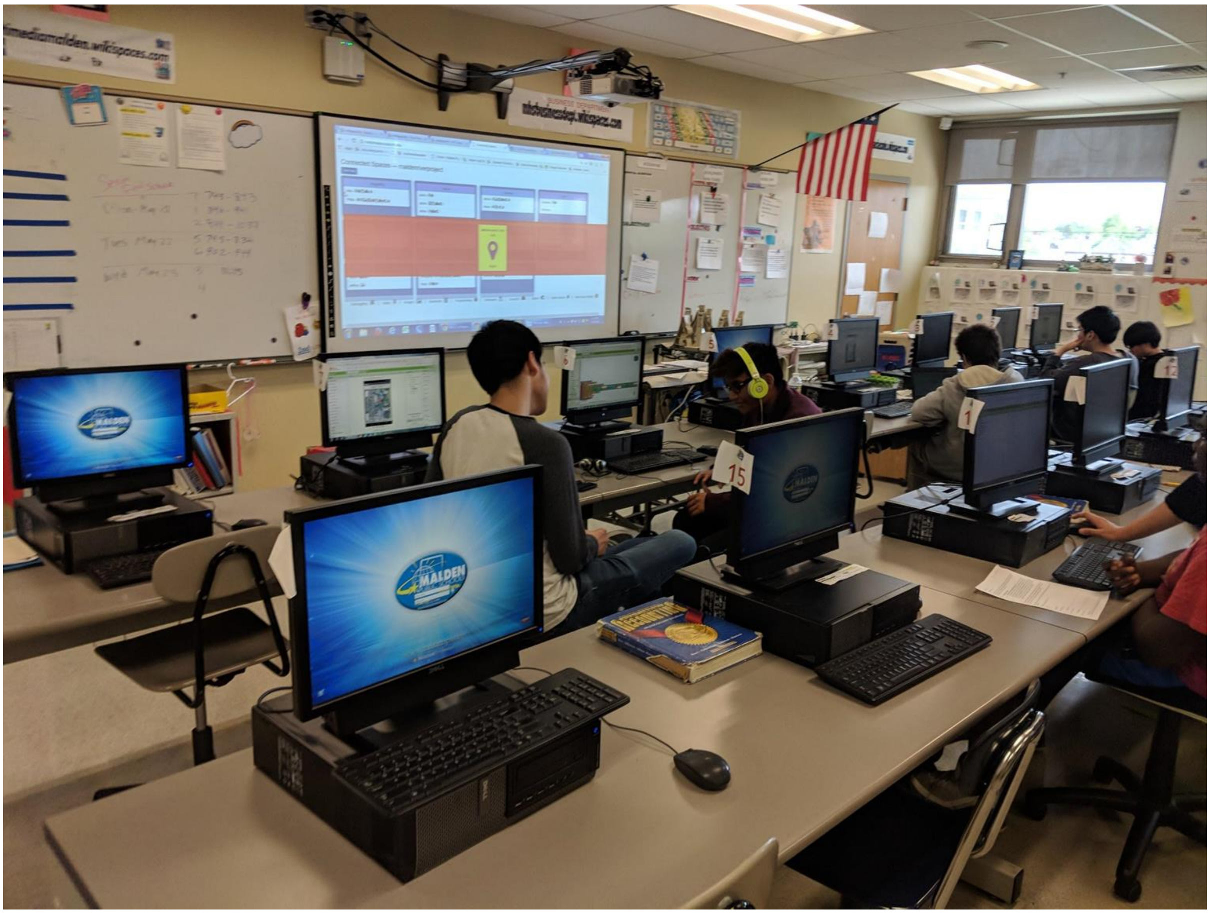


Figure 2. Photograph of the classroom of the study. This highlights how all students had individual computers they would work on. They would wear headphones for much of their individual work, which was intended to let them focus and watch tutorial videos or other content without disturbing the remaining class. These

headphones also had microphones which helped us collect data for this study. The audio collection was conducted following informed consent from the students and their parents. While none of this audio is used in this student, we did also work to remove any instance of voice from participants who did not consent to the data collection, even from others' recordings.

2.2.2. Technologies and Tools

a. MIT App Inventor

The students developed their apps using MIT's App Inventor (Patton et al., 2019), a blocks-based programming language, that allows students to build fully functional mobile applications without the need to learn complicated programming languages (Figure 3). App Inventor provides students with example codes to use the different modules (which span using the Maps API, Bluetooth services, Image Display, Camera, and many others). It also includes a repository of example projects which integrate different sets of modules. Lastly, it has a "Backpack" functionality which lets them copy and paste sections of code across different modules – supporting them in reusing their own code, as well as "remixing" code (as labelled in the Scratch interface – App Inventor's predecessor) from other projects and examples.

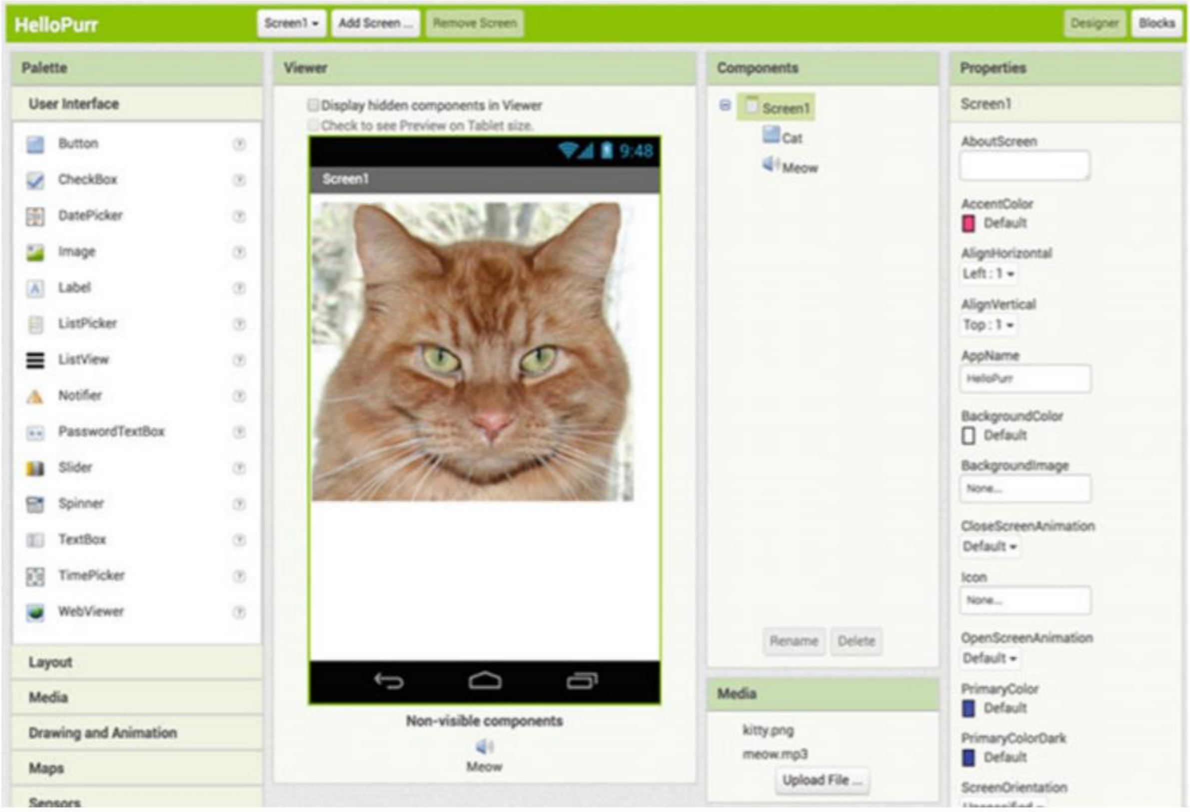


Figure 3. Screenshot of the App Inventor Programming interface in use

b. Connected Spaces

As described above, Connected Spaces (CxS) is an ambient awareness tool displayed on a large projection screen at the front of the class. CxS listed each student in the class in their project groups, alongside their personally identified affinities (Figure 4). When a student required help, they would access a help portal from their browser (Figure 5), and their corresponding help alert would appear on the main CxS portal (Figure 6).

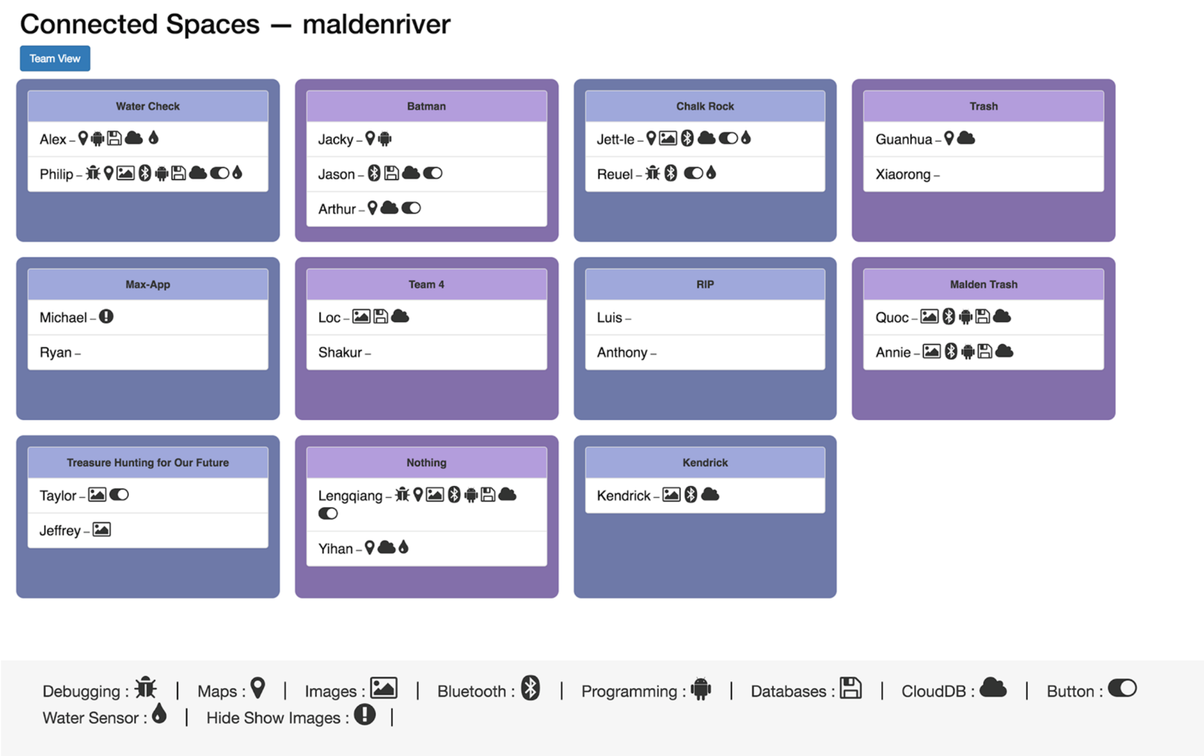


Figure 4. CxS's ambient display, also referred to as the "main screen" in our analysis, involves an "affinities list" (or "skill list") which lists all students' names, along with their self-identified affinities – topics relevant to their computing projects which they are interested in talking to others about. This data was collected by asking students to list "affinities" on a google form – aspects of App Inventor they felt comfortable talking about with others. This screen was intended to enable students to see their own interests in a concrete, public form, helping them identify with these. It also supported students knowing about their peers and being able to choose someone to approach to ask help from.

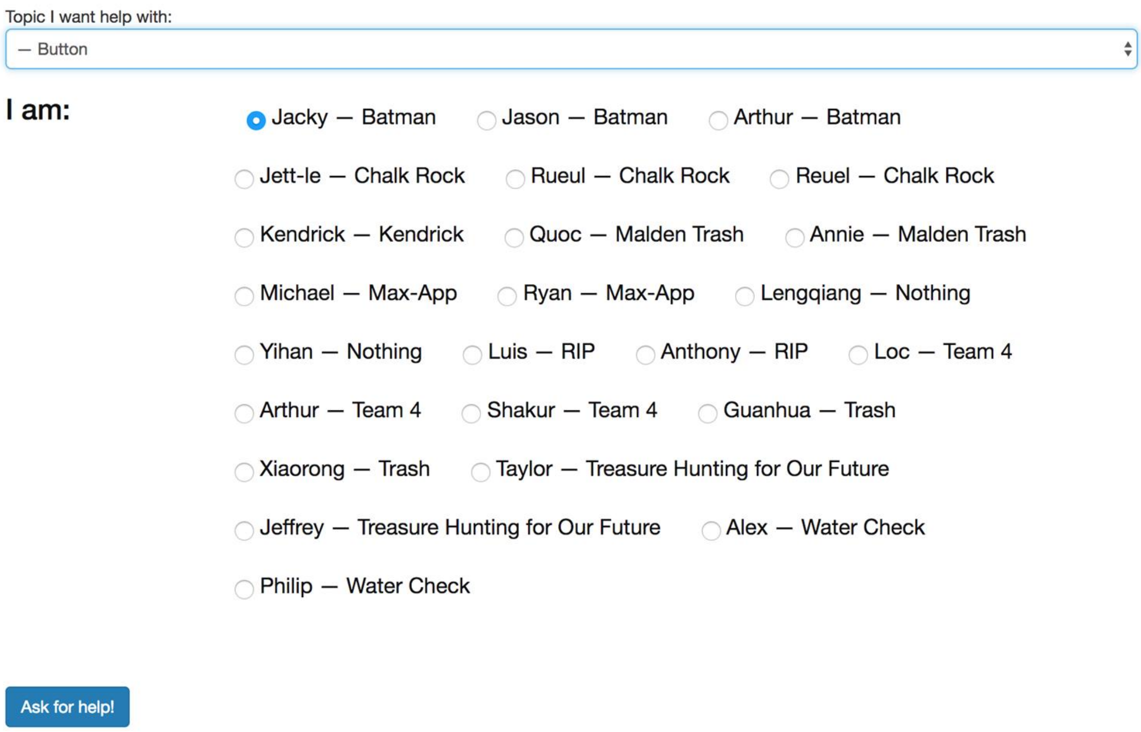


Figure 5. CxS's main screen is coupled with the help-seeking interface, available to all students in their browsers. Using this "help-calling" interface, they post calls for help – announcing their need for help in a particular topic. This appears as a large overlay on the Central Screen as shown in Figure 6.

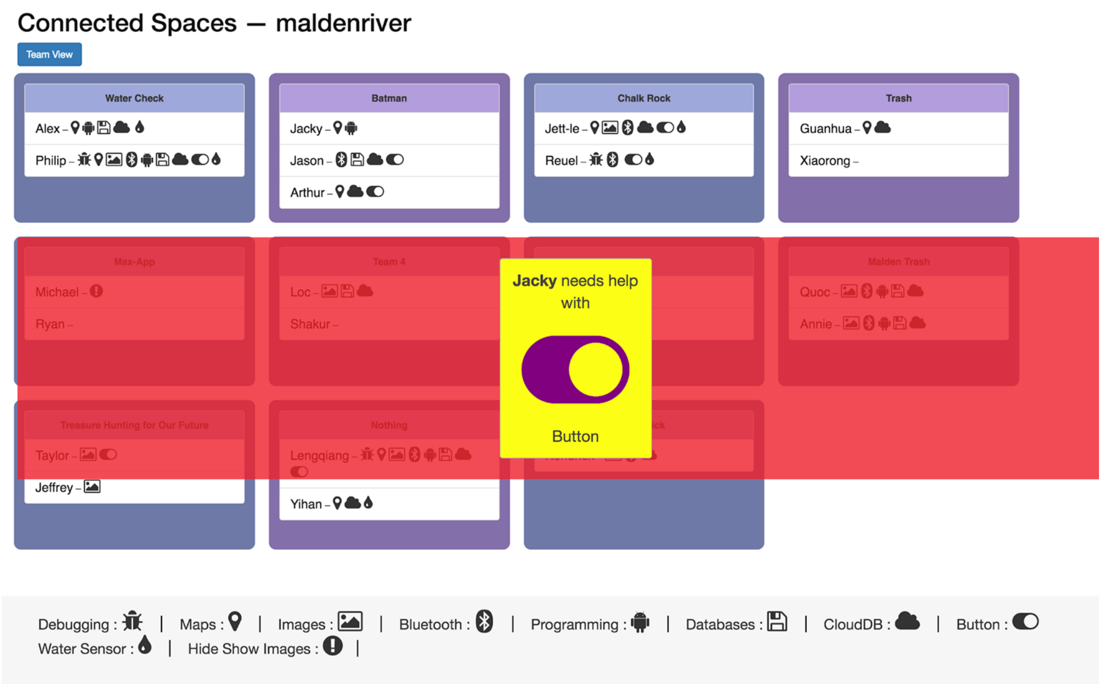


Figure 6. When a public help-call is made, it appears as a large hovering icon on the main screen, aimed to make everyone in the classroom aware that someone needs help. If another student feels capable of helping that student – in terms of having the requisite knowledge, interest, or availability – they always have the option to. The design for this call for help was aimed to enable students to declare their need for help without reaching out to other individuals, and also for students seeking opportunities to mentor others and voluntarily engage in co-inquiry to respond to others' calls for help.

2.2.3. Data Sources

For the students who provided consent, we recorded audio (using headset microphones) and screens (using Screencastify, a web-based screen recording software) as they worked. We also collected log data of all actions in App Inventor. Field-notes were taken by researchers well-versed in both App Inventor and CxS. Researchers acted as helpers to students as they built their projects.

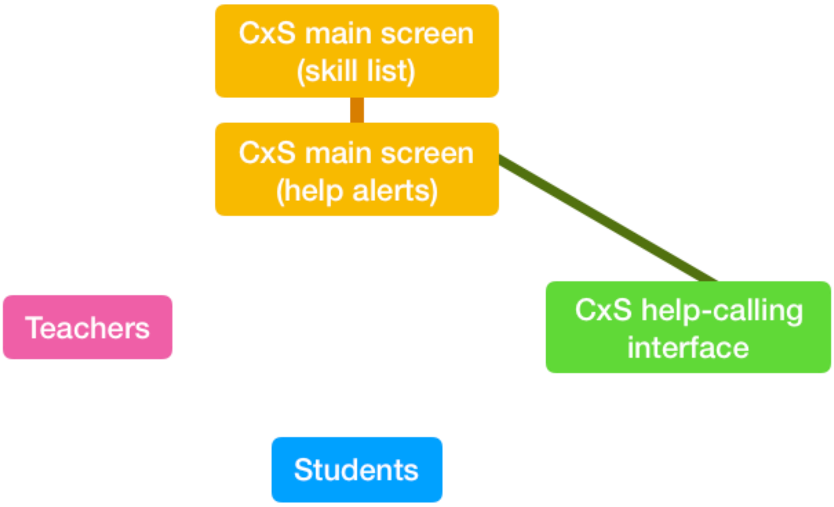
In this study, 'teachers' is used to refer to co-researchers who were the main designers and facilitators of the class and the App Inventor experts helping students when needed. They were also the main instructors for the first 5 weeks of the class introducing App Inventor and facilitating design exercises to help students develop project ideas.

2.3. FINDINGS AND ANALYSIS

In the following sections, we present observations primarily from the last 6 days of project work, after the tutorial classes, and students were in full swing working on their projects and Connected Spaces was running to enable them to ask each other for help. We present our ANT analyses and coupled design iterations of CxS in a temporal manner, to highlight the evolution of the classroom's network along with Connected Spaces. Alongside observations of each day's actions by the teachers, students, and Connected Spaces, we present a graphical depiction of the classroom's network (as pertaining to the research questions) as well as tabulated descriptions of the "current" state of the classroom network (as of that day) and the following design revisions the differences between the extant and desired network inspired.

2.3.1. Actor-Network Theory ⇄ Connected Spaces DBR implementation

For this ANT ⇄ DBR coupled analysis, we need a reference Actor-Network (Figure 7) of the target classroom behaviors our design aimed to achieve. This is critical in enabling us to be aware of how the network at any point of time is succeeding and faring, with respect to our design goals. At the same time, we were also prepared to adapt our target ANT – in terms of discovering new objects in the environment to be relevant actors, as well as attaining the desirable collaborative behaviors via different network setups.



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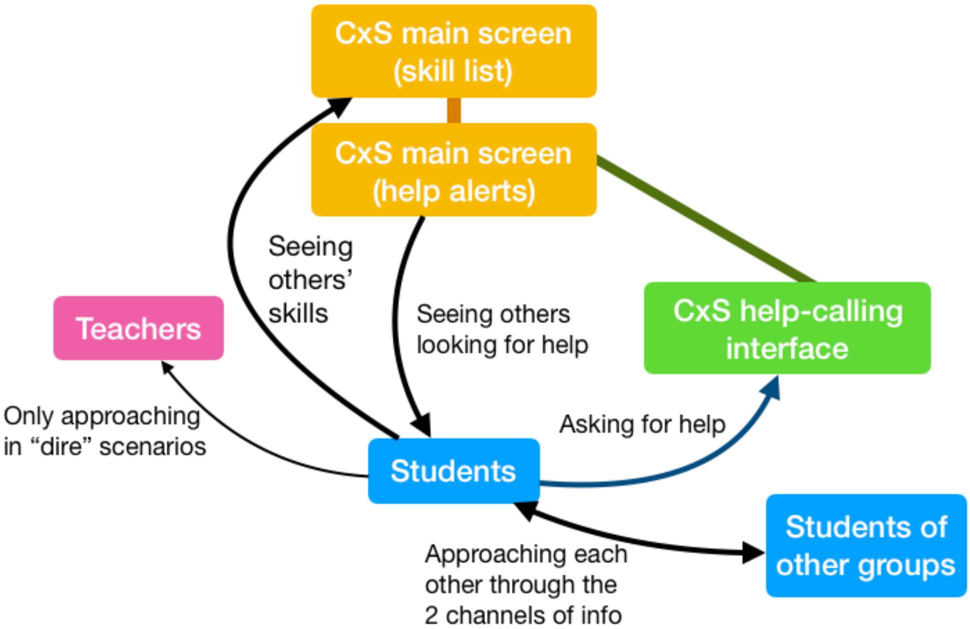


b.

Figure 7. a. In this study, we recognized that the CxS system, the teachers, and the students were the primary actors in the network relevant to our analyses of collaborative behaviors. **b.** Our desired actor-network relationships for collaborative learning using CxS: We expected students to autonomously use CxS to locate and leverage each other's knowledge. The skill list was intended for them to know who they could ask for help, the help calling interface was meant to make public calls for

help, and the help alerts were meant for students to see and help others in need of assistance, if they felt able or interested to. The arrows indicate the help sought (from an entity looking for knowledge towards one with the desired knowledge).

2.3.2. Day 1

Day 1 saw negligible usage of the CxS system. As the students were in early stages of project building, we did not present the CxS seeking help tool and only presented the list of student names with their affinities on the class's main screen.

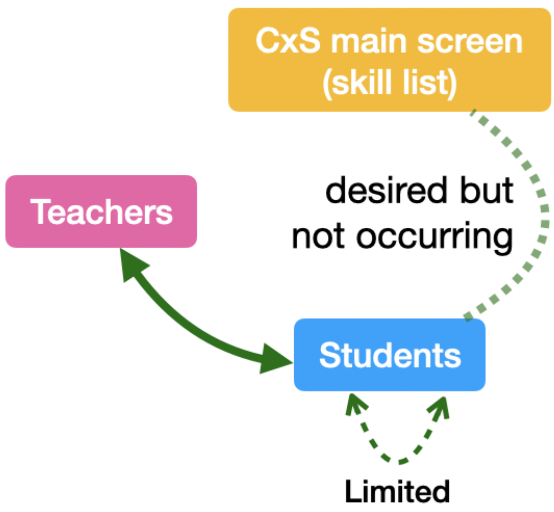
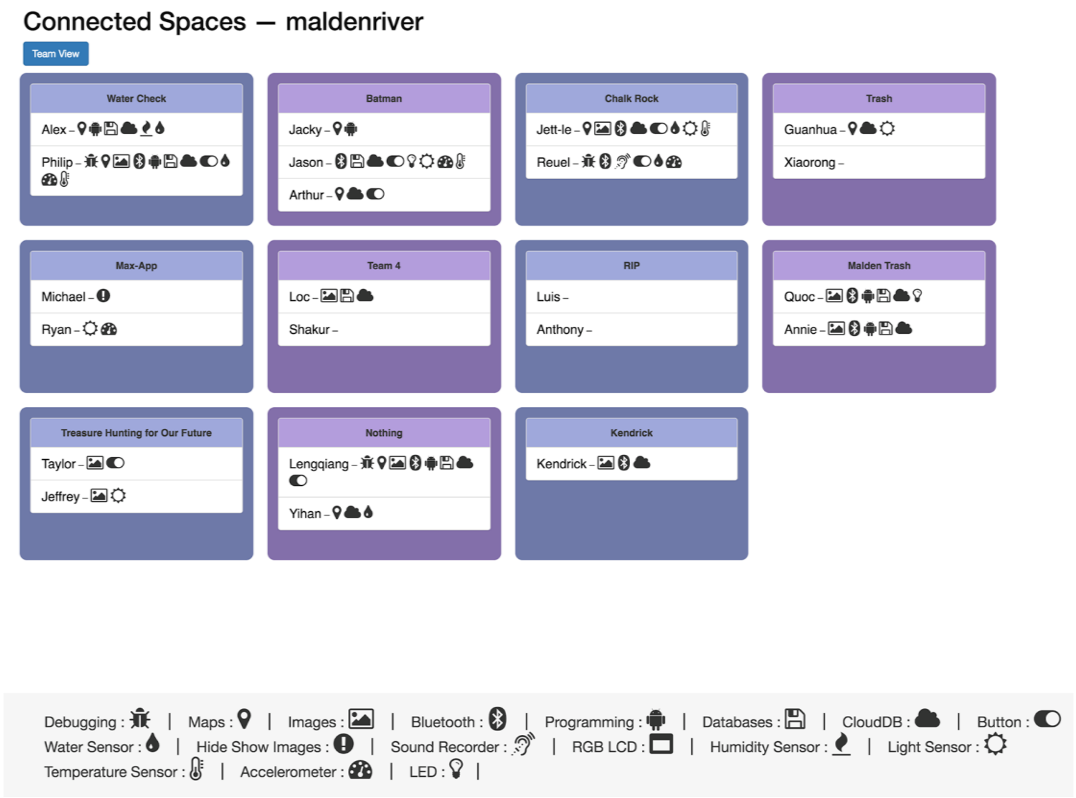


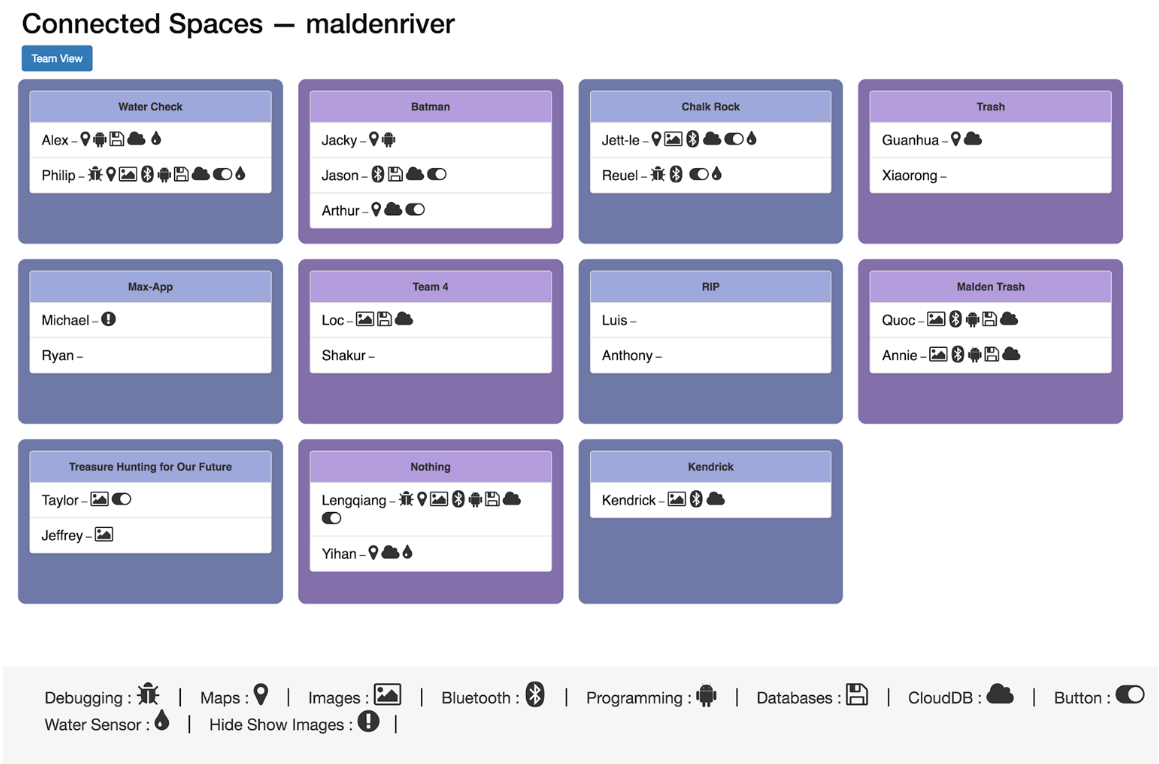
Figure 8. Day 1's network state. The dotted lines indicate a weak connection, and the translucent dotted line between skill list and students indicating a desired but nonexistent relationship. The arrows indicate direction of help seeking and giving.

Table 1. Day 1's observed classroom network, and associated design revisions

Network Description	**Design revisions**
At this point, the relationships between the actors mainly consisted of pairs working on their projects, a few across-group friends who would talk to each other, and teacher(s) who they would ask help from. We saw no evidence that students looked at the skill list or tried approaching anyone in the classroom outside of their project team, except for the teachers. This lack of desired usage made us re-evaluate CxS's design to see how it can be made more accessible.	The skills list had a large legend (22 affinities), with many (9 out of 22) students claiming over 4 affinities, making the display highly cluttered and hard to parse. These 17 affinities were at varying levels of specificities and emerged from students' own listing. After seeing the lack of usage of the CxS skill list, and also the difficulty involved in parsing it, we culled the affinities down to 10, hoping to make the list more usable (change depicted in Figure 8).


Connected Spaces — maldenriver
Team View
Water Check
Alex –
Philip –
Batman
Jacky –
Jason –
Arthur –
Chalk Rock
Jett-le –
Reuel –
Trash
Guanhua –
Xiaorong –
Max-App
Michael –
Ryan –
Team 4
Loc –
Shakur –
RIP
Luis –
Anthony –
Malden Trash
Quoc –
Annie –
Treasure Hunting for Our Future
Taylor –
Jeffrey –
Nothing
Lengqiang –
Yihan –
Kendrick
Kendrick –
Debugging : | Maps : | Images : | Bluetooth : | Programming : | Databases : | CloudDB : | Button :
Water Sensor : | Hide Show Images : | Sound Recorder : | RGB LCD : | Humidity Sensor : | Light Sensor :
Temperature Sensor : | Accelerometer : | LED : |

a.


Connected Spaces — maldenriver
Team View
Water Check
Alex –
Philip –
Batman
Jacky –
Jason –
Arthur –
Chalk Rock
Jett-le –
Reuel –
Trash
Guanhua –
Xiaorong –
Max-App
Michael –
Ryan –
Team 4
Loc –
Shakur –
RIP
Luis –
Anthony –
Malden Trash
Quoc –
Annie –
Treasure Hunting for Our Future
Taylor –
Jeffrey –
Nothing
Lengqiang –
Yihan –
Kendrick
Kendrick –
Debugging : | Maps : | Images : | Bluetooth : | Programming : | Databases : | CloudDB : | Button :
Water Sensor : | Hide Show Images : |

b.

Figure 9. a. Earlier version of skill list screen, with 17 affinities and excessive information density, along with a zoomed in version of the legend generated from student entered data.

b. The renewed version of the skill list, having culled overly specific affinities, leaving just 10 affinities to make the skill list easier to parse and use. This interface screenshot is also accompanied with a zoomed-in version of the refreshed legend.

2.3.3. Day 2

On Day 2, students were shown how to ask for help using CxS's web interface (see Figure 4, page 24). Log data showed three help requests were initiated by students almost immediately (within 20 - 40 seconds each) after showing students how to use the feature; however, these were quickly canceled and no interactions between students were observed, indicating that students were merely trying out the system to understand how it worked. This trying out the system early on is an important part of becoming familiarized with the system.

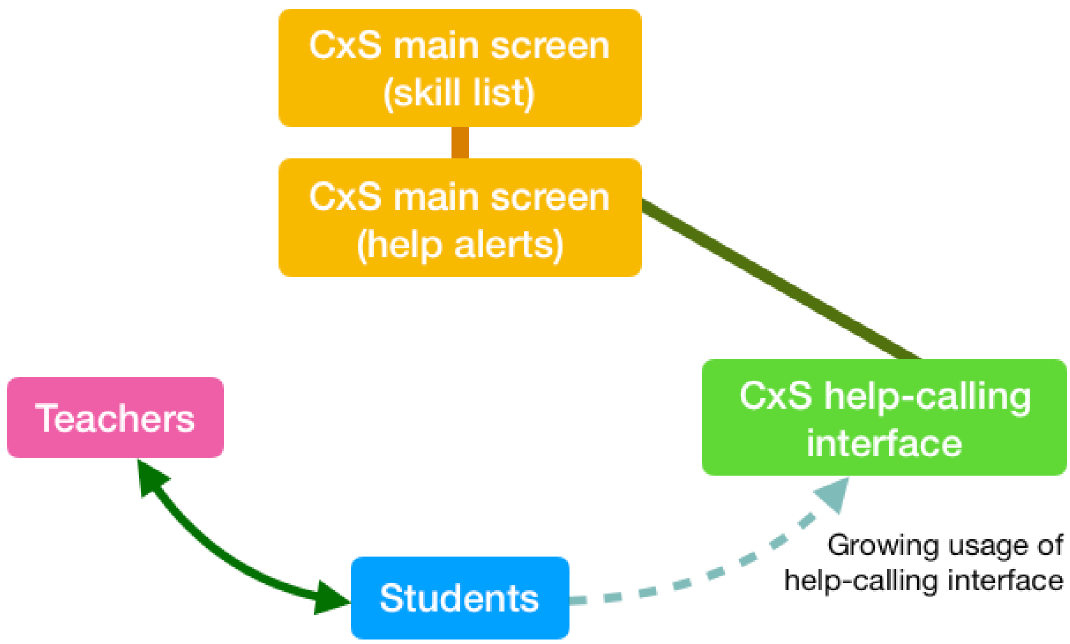


Figure 10. Day 2's Network state.

Table 2. Day 2's Network and Design Revisions

Network Description	Design Revisions
Students' gradual tinkering with the help calling interface began the transition to a more collaborative space. We still did not see any usage of the skill list, especially as the teachers kept playing a proactive role in trying to help students, as well as responding to students' calls for help whenever possible.	This state of classroom practices – strongly relying on teachers, willingly making calls for help but not reaching out to ask or offer help to other students – made us reconsider the likelihood of students using the skill list, given existent classroom practices and expectations of teachers being the

	established and accessible authority to seek and receive answers from. We redesigned the alerts to look far more “glaring”, and as teachers in the classroom, decided to try rerouting students’ calls for help to their peers whenever possible by using the help alerts and skill list.

2.3.4. Day 3

On Day 3, we saw increased uptake of students asking for help using CxS. While the researchers and teachers were responding to in-person calls for help, two different students made requests for help through CxS. Each request was resolved in around 2 minutes by the teachers (us) who saw it on the alerts screen and helped the students. At one point, the teacher asked a few students around if they wanted to help Drew who needed help with maps, but nobody seemed confident enough to solve Drew’s challenge.

Both help-asking instances involved students posting a call for help and hoping that someone responded to it. They did not proactively reach out to other students, nor did other students look at the skill list display to offer any help.

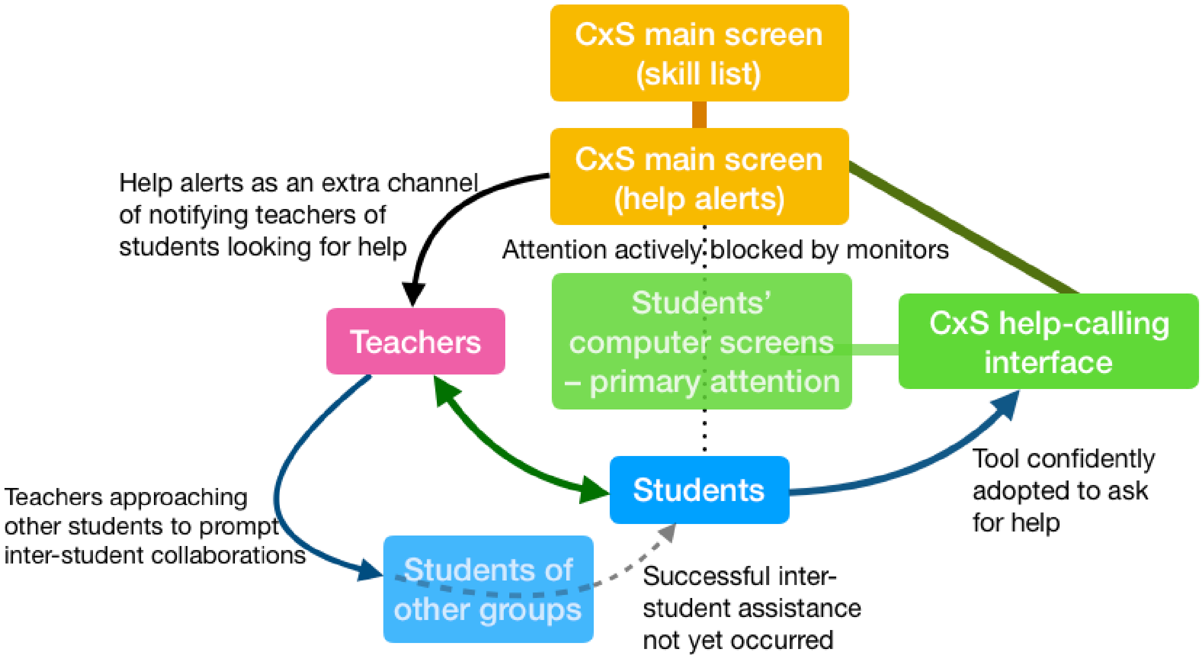


Figure 11. Day 3's Network state

Table 3. Day 3's Network and Design Revisions

Network Description	**Design Revisions**
Teachers became more involved users of the help alerts screen and attempting to form inter-student networks as described above and in Figure 7 (page 29). The students' relationship with the help-calling interface appeared to have solidified, though they did not	Apart from the lack of a cultural practice of attempting to help others in the classroom, it felt likely that the *main screen* aspects of the CxS tool were not being used as all students were focused on their own computer screens (depicted in figure 11 above), and not the central display which was only looked at when any teacher would specifically call

engage with any of the other parts of the CxS tool.

attention to it. We planned to try manually publicizing the contents of the main screen as much as possible, while trying to not distract students from their work. Since students were looking at, and using the help-calling interface, we implemented a potential helpers window beside the help-asking form as well – attempting to make it very easy to see who claimed confidence about specific topics a help-seeking student might be interested in (Figure 11).

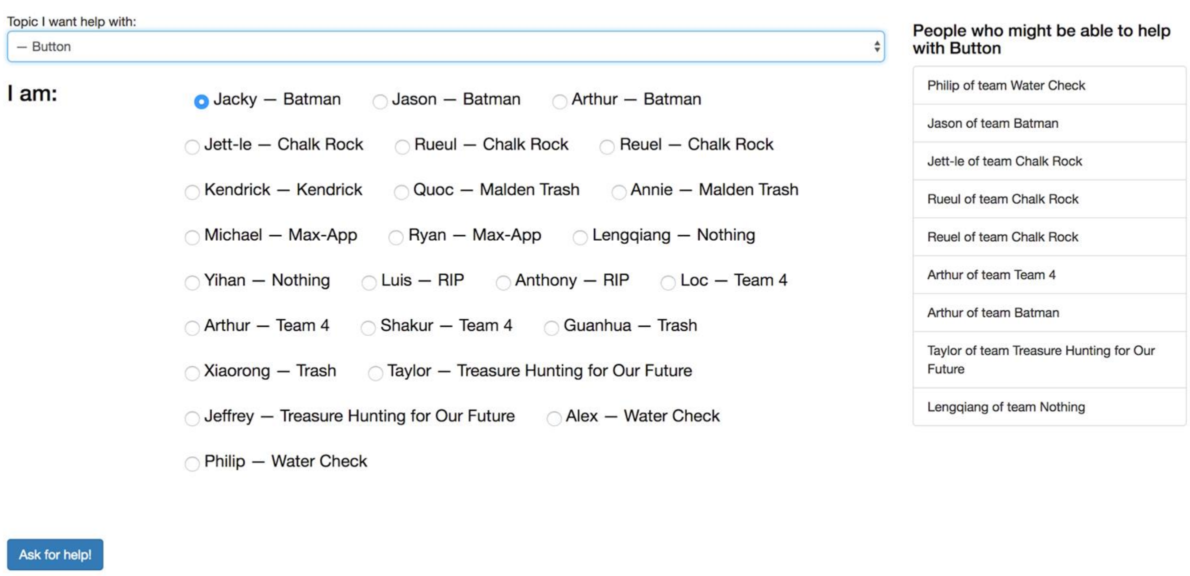


Figure 12. The right column of "relevant helpers" added to the help-calling interface, which would update on the affinity chosen from the dropdown of affinities.

2.3.5. Day 4 and onwards

On Day 4, we found greater mileage by focusing on mediating the relationship between students asking for help using CxS, and students capable of providing relevant help (through teachers' prior experience of coaching different students, coupled with information from the skill list). We also saw some students enthusiastically volunteering to help others, when the teacher saw a help request up on the screen, and loudly voiced it – "Who wants to help James with buttons?". A pair of students almost competed in claiming the opportunity to help James. One of the eager students went over to the student asking for help, and helped James make progress with his challenge.

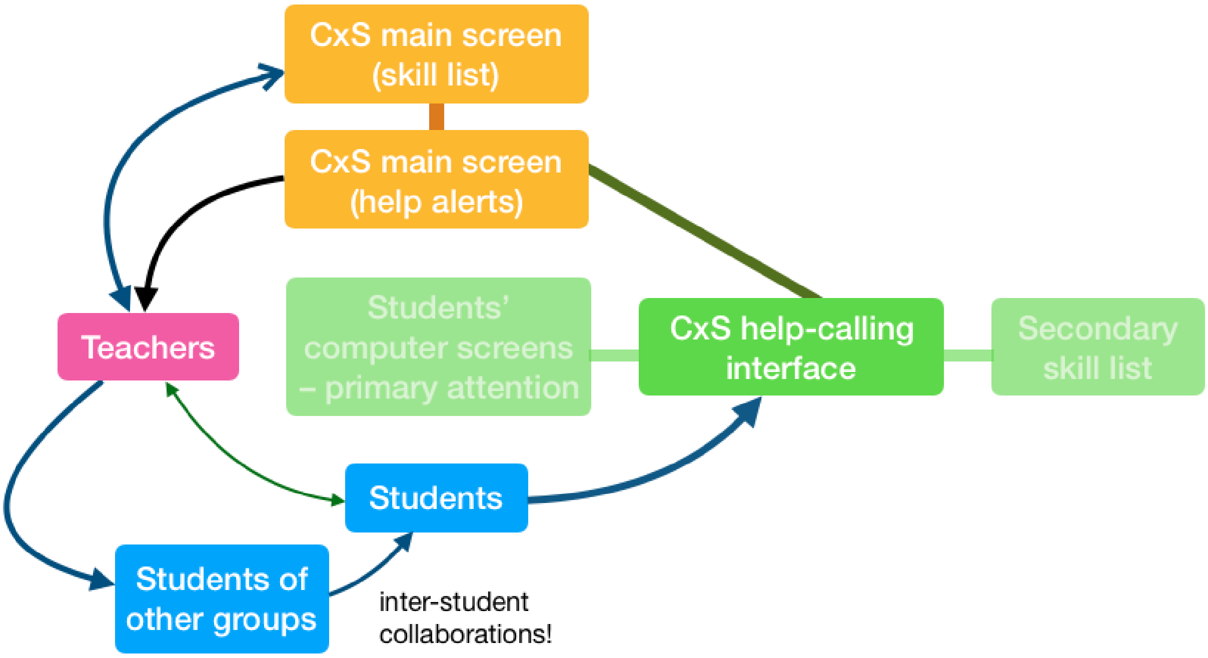
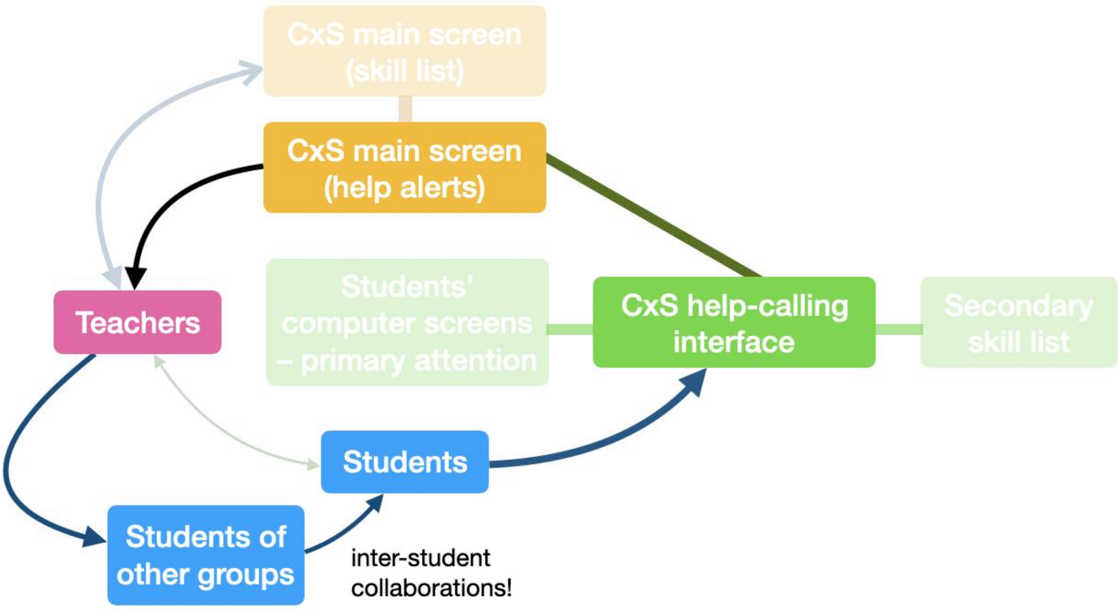


Figure 13. a. Day 4's Network State



b. The highlighted linkages in the same network diagram depicting how inter-student collaborations took place.

Table 4. Day 4's Network and Design Revisions

Network Description	Design Plans
Teachers were able to successfully use the skill list and help alerts for supporting students to collaborate and teach each other. Students showed no evidence of using the secondary skill list on their own displays, or proactively reaching out to each other for help (except for students with established friendships since before the class). The translation in teachers' roles as mediators of help-locators and connection makers, in contrast to the expected translation in students' roles, reflected the challenge of changing classroom behaviors in less than a week, without adequate incentives.	We began planning to adapt CxS's information displays and access systems, to be oriented more towards being parsed by teachers, and design tools and practices which can help teachers reduce their role as active help-providers, while making them more effective connection makers in the classroom. We expected that after experiencing an increased frequency of receiving help from each other successfully, students might reduce their reliance on teachers and seek help from each more directly over time.

2.4. CONCLUSIONS

The recognition of the role played by the positioning of the computer screen between students and the main screen's location was a salient example of how the ANT lens helped us notice unexpected objects as critical actors in the network. This contributed to our design understandings – how non-intrusiveness provided by ambient interfaces can err towards being ignored, depending on many different kinds of objects in the environment, and our designs and implementations need to be conscious of all other entities and their roles.

On day 4, when we publicly voiced a call for help ("Who wants to help James with buttons?"), we witnessed highly enthusiastic volunteering from other students. This enthusiasm was also observed in an earlier pilot test with Connected Spaces (Kumar, et al., 2017), which highlighted the value of public opportunities to help others in CxS; it suggests that young learners are eager to help each other but need to develop both the awareness of who to help and the confidence to do so. We need to design "triggers" that create conditions for students to exercise collaborative helpful behaviors. Classroom practices, and inadequate means for drawing students' attention to meaningful notifications seem to be major hindrances in students engaging in more collaboration.

Overall, we found the use of ANT in tandem with DBR to be highly valuable in helping us recognize how our designs did, or did not, facilitate the kinds of learning and collaborative behaviors we were aiming for. ANT was particularly valuable for helping us make the kinds of adjustments often advocated for by DBR during a study's enactment but are often hard to capture with analysis techniques that require significant amounts of data analysis or video coding. While further post-analysis is still critical for understanding the spectrum of interactions and learning that took place, ANT can provide a surprisingly rich on-the-fly insight into the relationships between students, teachers, and various supporting technologies. We feel this work is an important step in developing methodological approaches for supporting DRB research in technology-rich learning environments.

Chapter 3: SCAMP: An Analytical Framework for Examining Flexible Social Playfulness Around Interactive Museum Exhibits

3.1. INTRODUCTION

There is a need to identify an expansive variety of collaborative behaviors across different learning contexts. This expansion is not only critical for better recognition of different styles of engagement but also, relatedly, for sensemaking processes that different social configurations enable (Zimmerman et al., 2010). As interactive technology is integrated into learning environments to support more flexible participation for learners, there is growing interest and work in understanding how space and interfaces mediate access to information, understanding, and participation.

For this reason, we designed an interactive museum exhibit (*Rainbow Agents*) designed, in part, to support creative computer science learning across multiple social configurations. Our core research question for this paper is: **How can we better understand the relationship between the design of such technological multi-interface exhibits and the social configurations they support?**

3.2. RELATED WORK

Our work builds on work from across learning sciences, computer science, and museum studies. That said, our contribution is best framed at the intersection of research on collaboration in the learning sciences and the design of creative STEM museum exhibits.

This paper builds directly on previous work regarding social configurations (Enyedy, 2003; Roth, et al., 1999) which posits that physical space enables different roles and configurations. This groundwork is expanded through our use of Halverson et al.'s emergent forms of collaboration (Halverson, 2018) in open ended tinkering spaces, which shows how the design of a space towards "free flowing work" supports collaboration "through the air." Lyons et al. (2015) further suggest that the "visibility" of an exhibit – making visitors' participation and work easily seen, watched, and accessed – can enable those forms of collaboration in a museum space.

There is a significant body of work on social scaffolding in museums designed for family members. Gutwill & Allen (2010), in particular, suggests that the social configurations of family members may be more fruitfully flexible than previously assumed.

Hornecker et al. (2007) point to the opportunities that museums support for richer learning through shared participation, while Allen & Gutwill (2004) warn of the volume of challenges in designing for open-ended multiple user participation. Examples of these include: turn-taking, as a lack of input can lead to interference (Marshall, et al., 2009); the organization of access points may guide players/visitors into specific collaborations in unintended ways (Antle et al., 2013); and multiple inputs may lead to parallel play while avoiding collaboration (Inkpen et al., 1999).

Finally, with multi-user exhibits, there is an inherent tension between the value other visitors can provide via their performances – which often serve as exemplars or useful provocations (Meisner et al., 2007) – and the ways in which other visitors' actions serve to constrain or outright inhibit what an individual visitor can do or explore (Lyons, 2009). This suggests that exhibit design needs to allow for a flexible range of social configuration (Lyons et al., 2014). Not all visitors desire the same degree or type of social engagement, and even the same visitor can desire a different degree or type of social engagement from one moment to the next, which makes social exhibit design difficult. Interactive technologies – specifically those with multiple interfaces – offer the potential for supporting more flexible face-to-face social engagement (Sugimoto, et al., 2004). But the solution is more than just a matter of supplying a multi-interface form-factor. We need to better understand how to design activities and feedback and distribute these across interfaces to support a wide range of human-human social configurations (for e.g., from parallel to competitive to collaborative).

We investigate this line of inquiry through the following research question around our museum exhibit: How can the design of technological exhibits support emergent collaboration in a museum space between different sets of people – families, strangers, friends – which will in turn enable unique learning experiences through different social configurations?

In the following section, we describe the design of Rainbow Agents (RA) – our museum exhibit and the related data collecting process. This is followed by the introduction of SCAMP, the analytical framework proposed in this paper, and how it is derived primarily from Sandoval's Conjecture Mapping framework (2014). We follow that with two cases of collaborative play with Rainbow Agents, both involving a variety of social configurations enabled through the designed affordances of our exhibit. We end with a discussion about the value of SCAMP for supporting analyses specific to interactive museum exhibits and indicating opportunities for design revisions in productive manners for different kinds of social play goals.

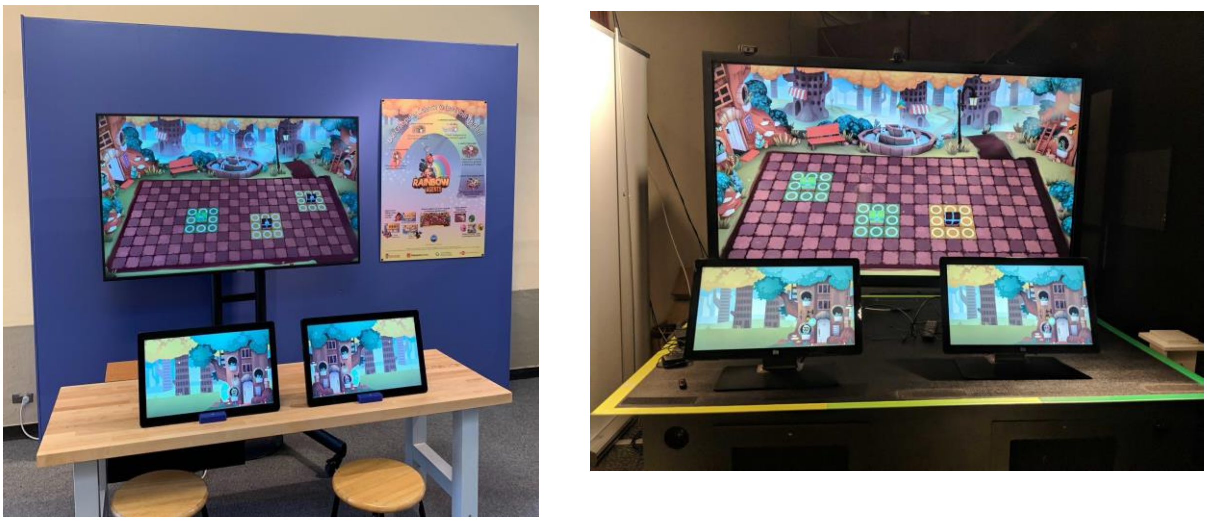


Figure 14. Pictures of the Rainbow Agents exhibit installation at the West Coast science museum (left) and the East Coast science museum (right)

3.3. METHODS

3.3.1. Rainbow Agents - Exhibit Design

The Rainbow Agents (RA) museum exhibit is a video game exhibit at two major science museums – one on the west coast, and one on the east coast. The exhibit consists of three screens (Figure 14). Two of these screens are touch screens that are placed on a table; two visitors at a time play the game with these touchscreens. The third, much larger, screen is the "shared community garden" that acts as the gameboard. This screen sits up against a wall behind the two other screens. In the museum on the west coast, there is a mounted poster on the wall next to the gameboard screen that offers information about the game, including basic gameplay, educational goals, and logos of the funding agency and project partners (Figure 14, left). The exhibit is placed against a wall along a corridor and visitors can approach or pass the exhibit from either direction.

The museum on the east coast is located in one of the most linguistically (and highly ethnically) diverse neighborhoods in the United States. The museum reports the demographics of the audience as 34% White, 22% Hispanic/Latinx, 20% Asian, 11% African American, 1% more than 1 race, and 3% other. Almost half the visitors are students as part of a school group, who are not charged for entry to the museum. Numerous other community programs, and free Sunday morning access are additional avenues designed to support increased cost-less entry to the museum. Spread across a large campus, and a 3 floor building, this museum is widely renowned for well researched interactive science museum exhibits and programming. In this museum, the exhibit is placed in a room near the start of the second floor, with a poster outside inviting visitors to play a game.

The science museum on the west coast is partnered with a well-known university in a mid-sized city. Serving approximately 140,000 visits each year (pre-2020), the museum has granted over 23,000 free admissions, offered approximately 1,500 onsite and offsite workshops to schools. Survey data indicates that 39% of the visitors identify as white, and attracts visitors ages 4-7 (41% of children) and ages 8-12 (32% of children). The Hall has a similar percentage of visitors with disabilities (10% compared with 8% nationally), a higher percentage of those have learning (31% vs 19%) or auditory (20% vs 11%) disabilities. In this museum, the exhibit is placed on the side of the lobby directly facing the entrance. This contributes to an increased visibility of the setup, different awareness about activity taking place.

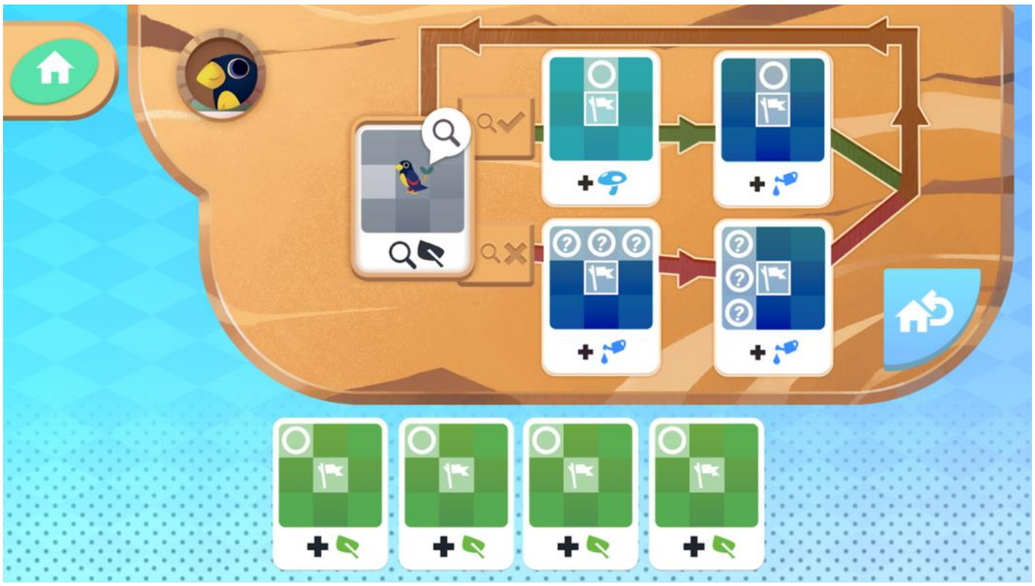


Figure 15. The state diagrams which represent the sequence of instructions the

garden agents follow (when programmed by the player). This image depicts the third agent, the bird's state diagram, which includes conditional and random logic.

Typically, when visitors approach the game they sit or stand in front of one screen or station. From there, they can select an "agent" to place on the community garden. Players then provide instructions to their agent using a computational "state diagram" (Gooch, 2008) to complete tasks (e.g., water plants or place a new plant) in the garden (Figure 15). There are three different types of plants in the game: woody plants, leafy plants, and fungi. Players are rewarded with a garden-wide thunderstorm when the garden has sufficient biodiversity across these plant types.

The game includes three "agents" that can complete tasks in the garden. Players typically start with one agent – the hedgehog – and, as they advance, are presented with the second and third agent. The hedgehog follows simple deterministic instructions ("place a wood plant in this location," "water in this location," etc.). The second agent, a salamander, introduces randomness: it has instructions that allow it to randomly select the location within a specified area to conduct its assigned task of watering or planting. The third agent, a bird, adds conditional logic: it first executes an assigned task, then searches nearby for a specified plant type. If it finds that plant type it executes one player-specified task, if it does not find that plant type, it executes a different player-assigned task. All these player actions can be completed with a single touchscreen and require no interaction or coordination with the other player.

Players are free to water any square and plant any unoccupied square in the garden. To encourage players to seed different kinds of plants, “treasure chests” appear at random locations and intervals with a fixed frequency (a new treasure chest every 10-15 seconds). These chests can only be unlocked by seeding specific kinds of plants nearby – increasingly difficult treasure chests need more plants in their vicinity to unlock. Unlocking treasure chests rewards players with a rainbow plant. Rainbow plants are only placeable by both players working in coordination. To place one, both players must select the button in the top left corner of the screen which will bring them to a new screen that includes a grid of the gameboard garden. On this screen, the player on the left can control the vertical position of the chest placement, and the player on the right can control the horizontal position of the chest placement. Once both players are satisfied with the chest position, they select a button to place the chest in the garden. This action is the only part of game play that *explicitly requires both players* to engage in the same activity at the same time. Choosing to place a rainbow chest is an optional act, however, and players frequently skip that choice.

The game includes no point system, levels, or fail states (although unwatered plants fade to grey before vanishing from the garden). Instead, the game invites players to create their own benchmarks for success and encourages a mixture of goals: aesthetic (garden beauty), achievement (how to open more treasure boxes or attain the rainfall), and learning (how to best use the more complex agents).

3.3.2. Data Collection (Includes Selection and Participation of Children)

This game is designed for middle schoolers. The first case discussed here was conducted at the museum on the East Coast. The poster outside the exhibit room informed visitors of ongoing recording. Researchers stood in the same room as the exhibit taking field notes and conducting semi-structured interviews with visitors who agreed to be interviewed. This case was selected using field notes and observing the multi-day recording data set to identify instances of social play which engaged a variety of social configurations.

For the second case presented in this paper, two museum docents conducted interviews with the players as they were playing in the museum on the west coast. The gameplay in this case initially centered around a middle schooler but also included their work with an accompanying adult, as well as much younger visitors who soon started playing beside the initial middle schooler. The interviews informed the visitors of the video recording and the exhibit’s research goals. This case is a result of selective observation from the docents looking for engagement from our intended audience and sampling from the notes. This focal case included 18 minutes of video data (close to the beginning, till the very end of the middle schooler’s gameplay), which is complemented by log data from the game, and observational notes from the docents. The log data collected includes all actions by the user, and states of the game, enabling us to analyze different levels of detail regarding in-game attempts, successes, and failures on the visitors' part.

This selective sampling to find cases of interest, is in line with the goal of this study - to illuminate the variety of social configurations made possible through specific design choices, and how to describe and analyze the strengths and shortcomings of different design decisions on the occurrence of these collaborations.

3.3.3. Analytical Framework: SCAMP

As described in our research question, our goal is to understand the relationship between design features and visitor participation.

Informed by the information outlined in our literature review and these observations of visitors at RA, we present a conjecture map (Sandoval, 2013) and a coding scheme to describe visitor engagement. Figure 16 presents the conjecture map for our project's design goals. While Sandoval's Conjecture Map tends to categorize Discursive Practices and Participant Structures as Embodiments and Mediating Processes, studying different forms of collaboration as emergent phenomena necessitates that we consider them as outcomes of the design. Under *Participant Structures*, we group different kinds of interpersonal roles (like Teacher, Observer, Partner, etc.), and *Discursive Practices* as play actions and durations.

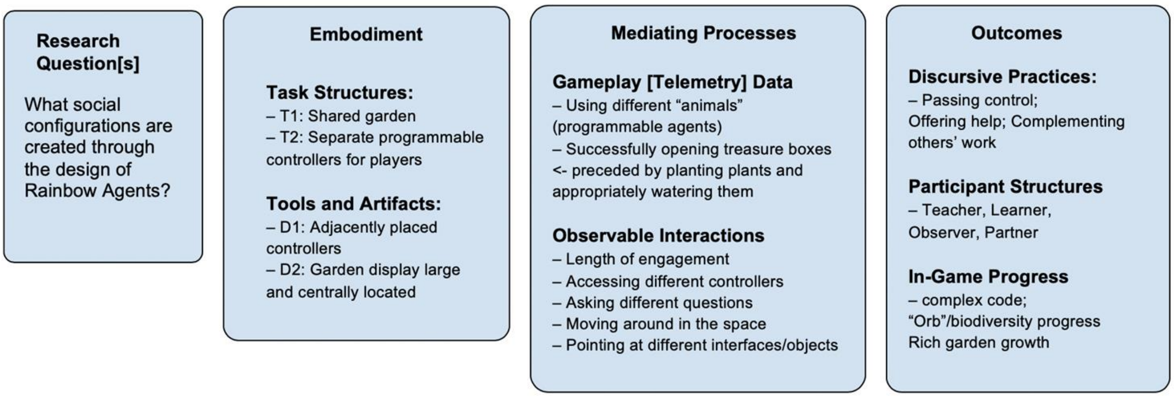


Figure 16. Conjecture map to inform the components of the SCAMP analysis – particularly through the embodiment of Rainbow Agent's design, and its affordances for creating different social configurations among visitors.

Conjecture maps are a commonly used tool in educational research to examine the relationship between the design of a learning environment and different learning outcomes of interest to the study. Conjecture maps provide a generalized model of examining these relationships, with no specific constraints on the sets of connections and outcomes that can exist. To examine the emergence of different kinds of collaborations around interactive museum exhibits, we created a specific conjecture map. Creating a coding scheme from this conjecture map helps us list and describe the different design-behavior relationships that emerge and has the ability to be used by other museum designers and researchers in the creation of specific research questions as well design ideas. We call this coding scheme SCAMP (Social Configuration Affordances for Museum Play). SCAMP involves recognizing social configurations of play around a museum exhibit using a coding scheme, and identifying relationships between the design features that support, hinder, or mandate certain social configurations (exemplified in Rainbow Agents and our cases).

Table 5. The SCAMP coding scheme – shorthand for codes to describe play events, and their relationship to design features.

Design hypothesis		**Goal Orientation**		**Play Action**		**Duration**	
Expectation	**Code**	**Action**	**Code**	**Action**	**Code**	**Action**	**Code**
Supports/Enables	E	Parallel	Par	Playing	P	Short	S
Mandate	M	Collaborative	Col	Teaching	T	Long	L
Hinder	H	Competitive	Com	Receiving	R		

We categorize *play events* as sections of an episode which appear to engender particular social configurations, i.e., a combination of a specific *goal orientation*, a *play action* (which describes a certain interpersonal role) for a certain *duration* (relative to other play events in the episode). This categorization/coding scheme is depicted in Table 5. Goal orientations here are not descriptions of the task design themselves, but how players are pursuing goals relative to each other. Often players will simply engage in their own goals (especially in the beginning) without paying much attention to what other players are doing. In this case, they might be pursuing different or common goals compared to their co-player, but we label playing in such a manner disconnected from their co-players, as *parallel* play. This might not appear to be *social* play, but we find that labeling it as an event is valuable in recognizing initial and intermediate stages of a process that flow through different social configurations. When players are working together – towards a shared goal while helping each other – we call this *collaborative* play (ascribing to collaboration as per Roschelle, 1992, and many others). When players are working on conflicting goals, we call this *competitive* play. As seen in one of our episodes, competitive play is unique that it can emerge without having designed competitive spaces. If there is access to similar sets of actions, players can engage competitively in doing the same action "better" than the other (however they decide to operationalize this comparison). Thus, it is critical to be open to recognizing competitive orientations, and which kinds of design features create space for the emergence of competition. In addition to this, it is also important to not consider competition as always undesirable, as it is a familiar form of engagement that can lead to productive learning experiences if the design of a learning environment guides them into effective learning opportunities.

The choices of *play actions* in this study comes from condensing Tissenbaum et al.'s (2017) DCLM framework – which include a variety of different social actions museum visitors engage in during informal play (Table 6). For this study, we want *play actions* to not be individual interactions that are typically momentary in nature, and instead convey a certain relationship between the interacting players. With this goal in mind, we describe the different play actions as *teaching* (combining narration, making suggestions, offering help), *receiving* (asking for help, receiving suggestions, observing others' work), and *playing* (interacting with the game).

Table 6. The divergent collaborative learning mechanisms framework

1. Mechanisms of collaborative discussion
    a. Making and accepting suggestions
    b. Clarification
    c. Negotiating
    d. Seeking help
2. Mechanisms for enacting divergent collaboration
    a. Joint attention and awareness
    b. Goal adaptation
    c. Boundary spanning actions
    d. Boundary spanning perception
    e. Narrations
    f. Modeling

Lastly, we describe the duration of these events as *short* or *long*. The duration of a play event is categorized depending on the length of engagement in a specific Goal Orientation + Play Action combination. This study differentiates between short and long events in relation to the different events within each episode, but these perceptions are also informed by broader work on the nature and context of the learning environment being studied. For instance, dwell times are often used as a first broad measure of engagement in museums. The length of time visitors spend at different exhibits is used as a measurement of what is considered more interesting or engaging. While this is complicated by the interactive nature of our exhibits, understanding common forms and spans of engagement in interactive science museums can be used to provide anchors for what makes a short or long play event. Recognizing which configurations last longer than others, combined with how configurations change over time, helps develop an understanding of the experiences of visitors at the museum exhibit.

The first column describes a specific set of relationships that are relevant for analyzing interactive learning tools, in particular such digital playful museum exhibits. In games and similar rich interactive experiences, different features or (game) mechanics encourage certain kinds of engagement, sometimes force specific actions, and often discourage other kinds of engagement. For instance, cooperative board games like Pandemic encourage players to engage in collective decision making, and discourage engaging competitively, or in parallel play. If players do not actively share resources and ideas with others, and choose to pursue their own strategy, they and their teammates are much more likely to lose. Some other cooperative board and card games like Mysterium, Bridge, and others *mandate* a certain amount of disjoint problem solving. The rules prohibit players for revealing information that they have unique access to, and players need to attain a shared goal with limited communication and a certain amount of parallel play. On the contrary, competitive games like Chess, have mechanics that hinder collaborative play while *mandating* competitive play. At the same time, the context of gameplay like a tournament, a tutoring session, or just friends playing, can engender many different social configurations despite being engaged in just competitive play (for instance, learning as a spectator, engaging in commentary and speculation, and teaching a student or peer while actively playing against them). Examining these connections between design features and different social configurations are the goal of this study.

To understand the connections between the design features and the occurrence of different social configurations, these codes need to be coupled with a description of the design feature that played a role in their creation. In SCAMP, we describe the link between design features and social configuration using a compact representation of our hypothesized relationships and observed events. In this work, we use the colors from the table to refer to the different columns: Plain for mechanic/design embodiment, Pink for design hypothesis's relationship, Green for Goal Orientation, Blue for Play Action (embodying different interpersonal roles), and Yellow for duration. We use a few additional symbols in this representation to convey additional information and ambiguous hypotheses. When a mechanic enables multiple behaviors, we describe it by listing the relevant collaborative interaction features together (for instance Col/Com indicates both Collaborative and Competitive behaviors, and * indicates all three Play Action types).

We describe the most notable relationships in Rainbow Agents here, going through the design features enlisted in our initial conjecture map (Figure 16 - Design Embodiment):

- T1 (Shared Garden as a *Task Structure*): E | Col/Par | * | * (Enables Collaborative or Parallel Play across different Play Actions and Durations.) We designed the shared nature of the garden to foster collaborative play across different play actions and durations. Workspaces where one's work affects and is affected by others' work leads to an awareness of and interest in what others are doing. In some environments, this interference can lead to reduction of coordinated action and participation when learners/participants feel like they do not have space or autonomy to do what they want to (Meisner, et al., 2007). This can push players into parallel play, or even leave the shared venture! But if player-learners are able to engage with autonomy, working on shared ground while doing similar but mutually additive work can lead to collaborative goal orientations. Since plants around treasure boxes reward both players, and plants across the garden reward the whole garden with a thunderstorm, the lack of individualized rewards encourages players to coordinate their work with each other.

- D1: (Centrally Displayed Garden as a physical aspect of the *tools' design*): E | * | T/R | * (Enables Teaching/Receiving roles across different goal orientations and durations).

We have seen how being able to access others' work in process (Lyons, et al., 2015) or even just creative products without seeing the process (Halverson, et al., 2018) helps the learning and work across others in shared learning spaces. The central, large nature of the garden is of unique consideration as it is not just shared by the two players, but openly visible to all museum visitors around. This plays a unique role in inviting new players, and providing opportunities for passive observation and learning, as well as collective sensemaking and teaching-learning interactions. Being able to see others' pursuits also creates space to see what goals others choose which often leads to adopting common or similar goals. This varies from taking the form of building on the work done by other players, and/or attempts to "best" them. In Rainbow Agents, this can take the form of trying to work towards a more vibrant shared garden as a joint effort or opening more treasure boxes than the other player as a competitive orientation.

- T2 (Separate Programmable Controllers): E | Par | P | L (Enables Parallel Play for Long sessions) Here the separateness of the programmable controllers is key to enabling parallel play for extended sessions. This is in line with Inkpen et al. (2009) finding that multiple input points lead to lesser collaborative play and more individual, disconnected play.

- D2 (Proximal Controllers): E | Col/Com | T/R | * (Enables Collaborative and Competitive engagement, particularly in the form of teaching and receiving actions of different durations) This hypothesis is in line with Marshall et al., (2009) and Antle et al. (2013) who found that overlapping and intersecting controls (in terms of proximity, number, and function) lead to players engaging with each other in a variety of ways.

Foregrounding these specific design features, demonstrates our focus on the object- and space-based nature of our analysis. A different SCAMP analysis could also focus on the specific interfaces and game mechanics and help understand how to design the game itself to support different social configurations.

3.4. RESULTS

3.4.1. Case 1

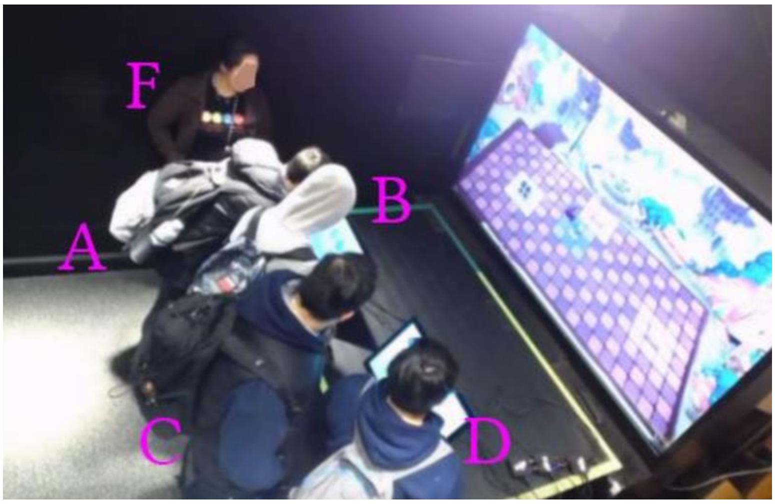


Figure 17. Stills from the first focal case's video recording depicting the main characters of the case at the East Coast science museum

Here we present a case of 5 boys who come into the room of the exhibit simultaneously, and transition through different forms of collaboration in their gameplay.

- D1/D2: E | Com | P | S (Centrally displayed garden and Proximally placed controllers Enable Competitive Play for a Short duration): The group approached the game and the players separated into two dyad groups (Player A & B; Player C & D – Figure 17). As the two dyads started to make sense of the game, they also tended to phrase the initial sensemaking process as a 'race', with each pair attempting to achieve the negatively interdependent goal-alignment of being the 'first' to figure the game out. Throughout this first phase of gameplay the two groups tend to move back and forth between sensemaking statements (stating potential hypotheses about the game's mechanics) while also engaging in similar competitive banter back and forth, for example after the above exchange there is an argument about which group 'got it right' first, with Player D saying, "We also got it right over here… More quickly than you."

In line with our expectations, the visitors perceived the arrangement of two controllers in front of a common screen as a stage set for competitive play. It seems plausible and likely that this (goal) orientation preference came from the familiarity of this setting to how video game experiences at home often look – with controllers in front of a television. This reinforces the need to be conscious of how the physical aspect of learning spaces' design has strong potential to set the stage for how learners would begin engagement. At the same time, this interpretation is not shared by all visitors. Some museum-savvy visitors prefer to look for written instructions or other guidance to orient their goals, and others with different game and technology experiences perceive this setting differently.

This tension across different interpretations is uniquely valuable in spaces like museums. Science museums were driven by the vision of providing rich complex learning experiences across a wider variety of audiences than is often manageable within the confines of school curricula (Oppenheimer, 1968). Despite this, there is adequate evidence that marginalization from museum cultures, access to science identities, and physical access to museums are some of the many reasons science museums and their exhibits are still often inequitable in who they engage and benefit (Feinstein & Meshoulam, 2014). This invites the need to disturb what museums and their exhibits look like, and what engagements they welcome in contrast to extant practices. These visitors' familiarity with the environment in a way that enables them to engage is a success, but it also needs to be examined closely around which visitors feel unwelcome in the presented space. While we have observed visitors engage with the game in overtly noncompetitive ways – where visitors spend extended periods of time working on watering plants with the goal for ensuring plant survival (Kumar, et al., 2020) – we need to be wary of the proclivity to read this arrangement of tools as a (competitive) gaming space, since video games (competitive ones in particular) are often perceived as fostering sexist and racist cultures (Leonard, 2006).

- T2 | E | Par | P | S (Separate Programmable controllers enabling extended parallel play coupled with) +

  D2 | E | Col | T/R | S (Nearby situated controllers enabling extended parallel play): After a brief clarifying conversation with the facilitator, the players begin to move towards increasingly coordinated play: with individual players directing the action of others. For example, Player A has a realization about the color coding of cards, saying, "So if we place [these cards] over here, we get mushrooms…" B asks a clarifying question to that statement, "Wait, how do you know you got to place them over there?" A clarifies his reasoning, "Because [the color of the cards and chest] match. Perfectly." B clarifies again, "Because they're purple?" and A agrees, further giving B an imperative command to execute on the screen, "Yeah. They match. Okay… so you just put purple in, and it'll work. Like… this one will go here [pointing]." C and D are developing their own understandings of the game. This represents both the parallel play enabled by separate controllers, as well as teaching/receiving opportunities by the proximity of their work to each other. Another implicit design feature that enables this conversation to be productive is the fact that their tools (each controller) is has similar abilities and mechanics of usage. As a result, they are able to individually *and* collectively make sense of a similar set of symbols, mechanisms and concepts.

- D1 | E | Par | T/R | S (Centrally placed large display Enabling Parallel Teaching/Receiving Short interactions) This co-development of understandings is exemplified as C and D continue to work in a different part of the shared garden. D is talking excitedly about his strategy, while C is not a very active player, but appears to be listening and responding. D points to the main screen, saying, "Ooooh, we need to get the [avatar] to go over there [pointing]." C shrugs, and unenthusiastically says, "Ok…". This also sets the stage for the beginning of collaborative play through the same designed affordance.

Here D2 | E | Col | P | S is represented for a short time as well: As the players begin to grasp the game and experience small successes, they start to work collaboratively as well – breaking out of the dyad structure and moving into a formation where all four players are actively working across both screens to communicate and formulate strategies.

As collaborative play becomes the predominant mode, the task structures become overt drivers of collaborative strategizing. T1 (Common Garden as a shared area of work) | E | Col/Par | P | L An example comes as Player D first realizes the plant wilting mechanic, saying, "[pointing at the main screen] Look, yo, the plants are dying out!" Player B looks up, and with alarm says, "Wait, the plants are dying!? … Wait, what does that mean?" Player D points again, saying, "Look, they're turning gray. … Go back to the other animals [meaning the simplest state agent] since they're dying out. Look, everything is turning gray." Both dyads work towards maintaining the garden, and after a few minutes their efforts pay off as they figure out the mechanism to unlock chests, triggering the collaborative slider mechanic, with all players providing input to the group description such as "You guys want to place it on a chest? One higher…" and, "No, one lower." Player A addresses the main group, saying, "I'll go there and help them out," and B connects with that, saying "So, it's a team effort, right?"

3.4.2. Case 2

Figure 18. Stills from the second focal case's video recording, at the beginning and the middle, depicting the main characters of the case, at the West Coast science museum

Here we present our second focal case, which began with a middle schooler in a grey t-shirt (herein called Gwen), beside an adult in a black jacket (here named Beth). Over the space of 18 minutes, Gwen almost always stays at her station, having placed and programmed the three agents 139 times. In contrast, Beth does very little work while sitting at her station for approximately 9 minutes, and then relinquishes control to Luke and Whitney – two much younger visitors in a grey shirt and a white dress respectively. They play for the remaining 9 minutes. Luke, Whitney, and Beth collectively place the three agents 59 times on the other station (herein called Station 2). This playthrough also sees two thunderstorms, at 10 minutes 30 seconds into the video and at 15 minutes 50 seconds. We use this as indicative that Gwen likely tried to cultivate enough plants to trigger the thunderstorm throughout her gameplay. The second thunderstorm is visibly triggered through the collaborative work of all three players at the two stations.

We now describe the 7 different social configurations supported by RA exhibit's design that take place in this sequence which consist of visitors negotiating participation and building understanding surrounding the game. We also pair those descriptions with a discussion around how the design features enabled the social configurations and the learning experience they provided.

1. D2 | E | * | T | S (Proximal player controllers Enabled Teaching interactions for a Short time regardless of Goal Orientation): Beth (likely parent) is an onlooker, hesitant to participate, while Gwen (child) is constantly working at her screen.

Four times she reaches across and controls Beth's screen: twice to control a collaborative game mechanic, twice to explain to Beth how to participate. 5 minutes in, Beth does make a few attempts to place an animal and program the corresponding state machine. This teaching of games from children to parents is a valuable and unique dynamic as it empowers children/young learners as holders of valuable knowledge that adults need or can use (Zimmerman et al., 2010). This is productively sustained for Gwen's growth in this particular interaction, as Beth is receptive and respectful of Gwen's explanations. This interaction can be described under the SCAMP framework with the description

2. D1 + D2: E | Par | R | L (Central Screen and Nearby controllers Enabled Parallel Receiving for a Long time span), coupled with T2 | E | Par | P | S (Separate Controllers Enabled Parallel Short Play): 6 minutes in, Whitney and Luke start hovering around Beth and Gwen. While being onlookers of the shared garden and the current players' (Beth and Gwen's) programming interfaces, Whitney tries to join in and participate through Beth's screen, especially since Beth is not actively engaging and only looking at Gwen's work (on Gwen's programming screen and the main garden). This is an opportunity for learning that is afforded by the visibility of tinkering performances in this space (Lyons et al., 2015). There is also an aspect of how the onlookers, initially peripheral participants to the exhibit's gameplay, become central participants through their self-insertion into the activity (Lave et al., 1991).
3. T2 | F | Par | P | * (Separate but Limited Controllers Forced Parallel Play across

different durations): 9 minutes in, Beth leaves screen 2 thereby relinquishing control to the hovering kids. This is reminiscent of the criticism of how limited controls can lead to competition over play (Marshall et al., 2009). The passage of controls in this case was smooth, but it did involve the kids waiting for a significant amount of time. As mentioned in event 2 (the last point), there was a shortcoming in the social norms of a museum as well as no designed affordance to support helping newer visitors participate. This presents possible design opportunities to encourage action on idle screens; and also, to structure opportunities to pass control.

4. D2 | E | Col | P | * (Nearby player controllers Enabled Collaborative Actions): Whitney and Luke share a seat and are seen smoothly negotiating control over screen 2. Whitney spends more time touching the screen, but both move between touching the screen, looking at Gwen's work on her screen, and the happenings on the central screen together as well as separately. These interfaces are designed as avenues for choosing and setting goals, as well as seeing other players' products and processes. Gwen continues to focus on her own screen throughout.
   Whitney and Luke engaged in a notably fluid transition between learning from their neighbors and taking control of the interface from each other. This kind of collaborative work and learning is uncommon among learners from dominant demographics in the US. Mejia-Arauz et al., (2018) observe young learners from families of Mexican heritage engaged as an *ensemble* – engaging in smooth nonverbal transfers of control between each other – during a problem-solving

activity, much more than learners of European heritage. This points to the need of expanding conceptions of collaborative activity, as well as the underlying values that are promoted as positive practices of collaboration. The design of learning environments should also enable support such a plurality of participation while being aware of the strengths as well as shortcomings of dominant collaborative practices like turn-based transfer and verbal communication of different processes and actions.

5. D2 (Proximal player controllers) | E | Col | P | * : Later during play, Gwen offers help to Whitney and Luke. This reflects Gwen expressing expertise, which has been gathered from her sustained work over the last 10 minutes. This offering of guidance, and pushes towards collaborative play is often designed for through task structures and discursive practices in other environments. Even in Rainbow Agents, there are task structures (like the reward and placement of rainbow plants) that are intended to nudge players towards active collaborative work. Antle et al., 2013 demonstrate the learning value of fostering such experiences, in their work with YouTopia which forces players to work together at certain junctures, so they have to discuss their understandings and goals with each other before proceeding.
6. T2 | M | Par | P | * (Separate programmable controllers Mandated Parallel Play): At the above offering of help from Gwen, Whitney says "Let's just do our own thing... and if we win, we can give each other a high-5!" In contrast with YouTopia's forced collaboration design (Antle et al., 2013), our design's deliberate affordance for parallel play leaves space for learning from each other, and also

allows for independent goals and sensemaking, rendering an experience unique to learning from multi-user museum exhibits. As we can see from these results, the players developed their own patterns of placing cards throughout the gameplay and tend to test out their own hypotheses based on their previous card arrangements as the pattern of using cards tends to become more complicated from the initial one card placement to the 2-card or 3-card combinations later on.

7. T1 + D1 | E | Col | P | S (Central & Shared garden Enabled Collaborative Play for a Short duration): Around 15 minutes in, while Luke is intently following Whitney's actions as well as Gwen's products on the shared screen, he points as he sees the different plant type orbs fill up. He calls attention to the upcoming storm, which everybody looks up to see, exemplifying joint attention enabled by the central shared screen which exhibits the products of each players' work.
   This event triggers conversation between the participants and they increasingly look at each other's screens. It provides an inroad into collaboration supported by the proximal controllers (D2: E | Col | * | *). Unfortunately, this case is cut short by Beth returning to move Gwen away from the exhibit, who is promptly replaced by another new player. Our video clip ends at this point, since all remaining players at the exhibit were noticeably younger than our intended age group.

3.5. DISCUSSION & CONCLUSIONS

The SCAMP framework allows us to examine how the design features interact with the observed play. Although one would expect two single screens to afford just individual, isolated play, our SCAMP description maintains consciousness of the value of the other controller's proximity and how this enabled collaborative play and teaching events across screens. Allowing players to become individual experts on their own screen allowed them to pass knowledge gained during solo play into a social context. It is notable how, repeatedly, in the second focal case (particularly events 1 and 5), parallel play prompted teaching and receiving events and collaborative actions. The development of independent expertise across different players was particularly well suited to teaching each other about the progression of events of the solo play. This supports prior work on the value of parallel learning enabling richer collaboration.

It is evident that none of the described features necessitate collaborative play, beyond a few interactions. Despite that, what we see is that the minimal prompting of collaborative events – like the thunderstorms that are triggered by everyone's work and affect all plants in the garden – tend to prompt further unforced collaborative play and teaching among players. Once the "play ice" has been broken, the players are much more open to playing collaboratively. This takes place in both our cases: collaborative play and joint attention (Tissenbaum et al., 2017) emerges despite explicit claims for parallel or competitive play earlier.

Our initial hypotheses were reasonably simple and well supported by the literature, but they fell well short of the observed behavior through unexpected interactions between the design features.

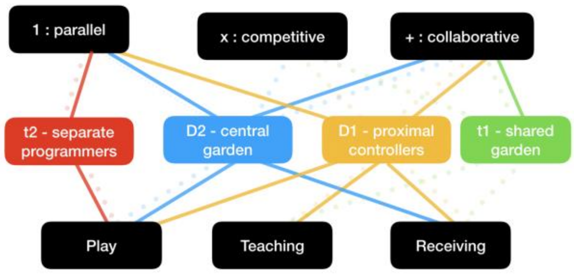


Figure 19. The dotted faded lines depict the expected affordances of the design features, and the solid lines are the ones observed in this case. Most notably, D1 and D2 (the Central Garden and Proximal Controllers) afforded Parallel | Receiving – the benefit of learning as an onlooker when other players' tinkering is available for public viewing (Lyons et al., 2015).

In addition, the end of case 2's event 7 marks an interesting form of Collaborative/Parallel Play, afforded by D2 (Proximal Controllers), where without any articulated Teaching/Receiving, or even goal coordination (Roschelle, 1992), the players being aware of each other's work enabled them to pursue overall "win conditions". This is particularly enabled by mechanisms within T1 (the shared garden) where both treasure boxes, and orbs corresponding to biodiversity, are affected by both players positively and reward both players' work and gameplay simultaneously.

The timeline of events in case 2 is:

D2: E | * | T | S

D2 + D1: E | Par | R | L

T2: F | Par | P | *

D2: E | Col | P | *

T2: F | Par | P | *

T1 + D1: E | Col | P | S

D2: E | Col | * | *

The way in which instances of parallel/solo play flow into collaborative play (and other interactions) becoming more common, is a reflective case of how active social engagement becomes more common.

In this case, and other informal observations, we have found that the collaboration sticks around, in different *flavors*, and students continue to teach and cooperate while acting with varying amounts of independence. Our suggestion is then that the design elements afford 'stickiness' – that is, the degree to which social configurations persist. It is not surprising that people collaborate more once they have successfully collaborated, but the SCAMP-support analysis highlights design research possibilities of specific interest.

More research is needed to explore which design features prompt more or less sticky/persisting collaboration. When does the social configuration persist across the session? For whom are the social configurations sticky? Which configurations are more "naturally sticky" (i.e., if they happen with design prompting, they are likely to happen again) and which configurations only become sticky after multiple design events?)

In further work, we hope to tease out a more complete picture of SCAMP and when SCAMP prompts the stickiness of social configurations. At the same time, the popularity of dark design patterns in many game-like environments (Zagal et al., 2013) pushes us to be cautious of how we design for sticky modes of interaction. Future work extending SCAMP analyses need to integrate measurements of learning and progress and differentiate between more and less valuable social configurations in different environments.

Chapter 4: Different Collaborations towards Interconnected Sustainability

4.1. INTRODUCTION

Given the increasing impact climate and environmental events are having on lives, communities, economies, and the world at large, there is a rising need for climate science and sustainability education (Egger, Kastens, & Turrin, 2017; National Research Council, 2013). Climate and environmental sciences cannot be understood abstracted from the interconnected political, economic, social, and ecological priorities that drive them (Hollweg et al., 2011). For instance, politics often drives economic systems, which in turn, leads to key decisions about planning and growth. These decisions can then have far reaching ecological impacts, which in response, affect both the economic and social systems. In addition, the factors within a region and its environment are not siloed; the decisions of different territories managing their own economic-ecological-social systems directly and indirectly affect each other, particularly when they rely on shared resources to help and compete with each other. By designing learning experiences that incorporate multiple disciplines using interdisciplinary and integrated approaches, we can enable students to develop the sophisticated problem-solving skills they need to solve large-scale problems in the present and in the future (Madden et al., 2013).

An underemphasized aspect of learning about such complex systems in real worlds is the actual experience of negotiating across different parties with competing interests. While educational research has shown some effectiveness in supporting learning about complex systems through computer, and even networked collaborative games (Dearden & Wilson, 2011), their screen- and location-locked interfaces limit the kinds of face-to-face interactions that sit at the core of these complex systems (Kreitmayer et al., 2012). In contrast immersive multiplayer games hybrid (combined digital and physical) games and simulations can leverage space and movement in a classroom to embody the geographical distribution and interdependence found in ecological systems; as well as enable discussions and conversations at varying levels of privacy that emulate economic and political negotiations (Squire et al., 2007).

In this paper, we present an immersive whole-class multiplayer city management game that supports learners in enacting and understanding these interdependent ecological, political, and economic systems – through their planning and developing their own cities while simultaneously collaborating, cooperating, and competing with their peers as they grow and sustain their own cities' development. In these kinds of complex-system simulation environments, this development of understanding is reflected in learners making increasingly strategic decisions, within and across teams. To recognize and understand this, building on emergent dialogue (Antle et al., 2014) and procedural rhetoric (Bogost, 2008), we developed and applied a lens of *procedural collaboration* – identifying evolving understanding by observing the increasingly complex ways learners strategize and collaborate with each other (within and across teams).

4.2. BACKGROUND

4.2.1 Participatory, Collaborative Simulations

Games and simulations have been shown to be effective in supporting a range of disciplinary learning (Holbert & Wilensky, 2019; Strawhacker et al., 2018), facilitating personally-relevant connections to underlying STEM and humanities content (Lenhart et al., 2008), increasing students’ positive attitudes towards science (Verish et al., 2019), enabling them to engage in creative collaborative problem-solving (Strawhacker et al., 2018), and increasing their engagement with content while achieving the same learning gains as traditional instruction methods (Annetta et al., 2009). Management games and simulations, in particular, have shown potential to situate learners as the drivers of systems phenomena, and provide opportunities for player-learners to critically reflect on the role their actions have on the larger interconnected system (Dearden & Wilson, 2011). However, many of these games and simulations are locked into single-player formats, or multi-player interactions that restrict peer-to-peer interaction through screens, limiting the kinds of face-to-face interactions that are at the heart of many topics' complexity (Kreitmayer et al., 2012).

In response, participatory simulations provide a particularly fertile approach for students to collaboratively engage with and learn about complex systems (Wilensky & Stroup, 1999). Participatory simulations enable students to act as individual agents in a system and reflect on the system-level phenomena that emerge through their individual and collective agent actions. Participatory simulations often leverage the physical space of the learning environment, by situating elements of the phenomena under study across the room's physical layout and connecting them students' own location in the room. Further, these simulations often respond to students' proximity to these elements and their peers, which can then directly impact the overall phenomena. For instance, in Colella's (2000) work, students were outfitted with microcontrollers that tracked their respective locations in the room, and when students came in close contact with their peers, to model the underlying concepts around how diseases spread.

A similar approach to participatory simulations is immersive simulations (Lui & Slotta, 2014). Immersive simulations leverage the physical space by transforming the learning environment into an immersive instance of the phenomena under investigation, creating a mixed-reality experience for the learner. For instance, in Wallcology (Moher et al., 2008) students interact with wall mounted monitors that act as virtual lenses into their classroom walls, allowing them to investigate ecologies of simulated bugs that "live" throughout the classroom. In EvoRoom (Lui & Slotta, 2014), students are immersed in Borneo and Sumatra rainforests as they investigate ecological changes over millions of years. While the depth of immersion can vary across these simulations, studies have shown them to be effective in drawing learners into the scenario under investigation, making it more personally relevant and meaningful (Becu et al., 2017). Taken as a whole, these kinds of immersive simulations are well suited to support rich collective inquiry around phenomena or systems that are hard to engage with in the real world, as they are able to foreground features salient to the desired learning goals.

4.2.2 Diverse Collaborations in Learner-Driven Immersive Simulations

As mentioned above, face-to-face, immersive simulations can allow learners to engage in the kinds of direct person-to-person interactions that lie at the heart of many complex phenomena, which in turn, provides opportunities for unique forms of spatially-dependent forms of collaboration to emerge (Halverson, Litts, & Gravel, 2018). For instance, students at one end of the room tend to interact with those near them and connecting or collaborating with others requires students to physically move across the room (in contrast to digital environments where space is a non-factor), potentially moving them into new contexts or settings, or even changing the simulation itself. For instance, in BeeSim (Peppler et al., 2010) young learners role-playing as (virtual) bees move around the classroom looking for nectar to share with their hive. Between each round of the simulations, students must work with their peers to nonverbally communicate which flowers in the room are the best for collecting the nectar. Where they move in the room, and which flowers they interact with, directly mediate their understanding of the phenomena. In RoomQuake, students work together to capture the seismic activity across their classroom, sharing their respective data with the rest of the class to triangulate and find the virtual fault line running through their class (Jaeger et al., 2016). However, not all face-to-face simulations and games are inherently collaborative through their mechanics. For instance, in Oztoc, a museum simulation in which visitors are tasked with constructing electrical circuits to capture and catalog fictional fish, participants are free to move between independent and collaborative modes of investigation. In many cases, visitors were observed engaging in divergent forms of collaboration, in which they collaborated for short periods to achieve complementary outcomes, while aiming to complete individual and divergent goals (Tissenbaum et al., 2019). These examples demonstrate how simulations and games developed for physically co-located play are able to foster learning through a rich variety of collaborative engagements.

At the same time, while many simulations have students working together at varying capacities – from constant teamwork to just parallel play – in pursuit of developing their collective knowledge, designed competitive play is often overlooked or avoided as a learning configuration. Taken on its own, competitive gameplay can lead to lesser engagement and poorer sensemaking in educational games, when compared to games centering collective action and understanding (Peppler, Danish & Phelps, 2013). This is due in part to the fact that in most competitive games, individuals pursue their own success, either disregarding or explicitly contesting others' success or progression (Janssen et al. 2010). However, some critics have argued that this is due to inherent flaws in the design of such activities, such as a "winner take all" approach, or the failure to get learners to consider the potential longer-term goals of their decisions beyond when the gameplay ends (e.g., promoting sustainability) (Fennewald & Kievit-Kylar, 2013). However, there is limited work that examines environments where participants can flexibly move between competitive or collaborative forms of play, allowing learners to identify for themselves the advantages and shortcomings of each approach.

4.2.3 Learning from games: Procedural Rhetoric, Emergent Dialogue, and Procedural Collaborations

The need for foregrounding *choice* around forms of collaboration through simulations and games is bolstered by the unique value proposition of games – their ability to convey ideas in an *enacted* form. Bogost's concept of procedural rhetoric (2000) presents how the rhetoric of games – their ability to convey an idea or depict a story – is uniquely empowered by their participatory and choice-laden nature. By embedding player actions within a designed space of constraints and affordances, game designers convey a specific vision of how a world works, and similar to other kinds of rhetoric, players' engagement in this possibility space defines the specific understandings they take away from their gameplay. For instance, in the classic simulation game Civilization (Firaxis Games, 2003), players (in single or multiplayer modes) choose how their respective civilizations grow, interact with other civilizations, and ultimately succeed or fail. The ability to choose different pathways of progress, and ways of victory – colonization (through land control, interstellar travel, or military conquest) or diplomacy – represent a variegated but particular set of ways that represent success in the game, and the sequences of choices and strategies players undertake represent (simplified) understandings of how such progress and "victory" can occur in the world.

While these kinds of games can support students to engage in productive discussion with their peers (Lee & Probert, 2010), it may require significant outside scaffolding, and in many cases, students can play the whole game with limited direct discussion or coordination with peers. In this context, Antle et al. (2014) argue for the educational value of *codependent access points* – design elements which force players to coordinate disparate pieces of information about a complex system to make an effective decision – as an avenue to enact social learning through design-triggered conversation. These access points create space for differential perspectives across the participants, which are leveraged to generate rich conversation about the whole system, termed *emergent dialogue*. For instance, in their tabletop learning simulation YouTopia, students work together to make decisions about how to grow their city and collaboratively discuss the impacts of their individual decisions on the desired decisions to be undertaken by their co-players. A critical component to codependent access points is that while it encourages collaboration, it does not force it, giving students a certain level of autonomy in their collaborative discussions (Fan et al., 2014).

Inspired by Antle's design recommendations and the underexplored nature of learning complex systems phenomena as embodied in different forms of collaboration, in this work we propose the concept of *procedural collaboration*. As described by Bogost (2008), the nature of the collaboration underlying a game is integral to the systems understanding it fosters – playing partial information cooperative games like Mysterium build different communication skills, in comparison to full information cooperative games like Pandemic. The conversational dynamics and underlying strategies are similarly different in competitive games like Scotland Yard (partial information) and chess (full information). In these games, the collaboration mechanic only occasionally reflects how the real-world system being emulated works. In Pandemic, players play a team of researchers, medics, and other medical workers and managers making collective decisions to mitigate the spread of an infectious disease. This simplified cooperative mechanic presents a specific model of how different expertises could work in synchronicity to fight a pandemic. For the sake of gameplay and design, it does not engage with the potential of competing interests held by different nations, organizations, and stakeholders in such an endeavor, which strain decision making and coordinated productive action. As a result, Pandemic chooses to engage in learning through only one kind of procedural collaboration – the ability of a fully coordinated and positively interdependent team of medical workers in fighting the spread of a disease.

In this spirit, we describe *procedural collaboration(s)* as modes of engagement which represent system phenomena which are also learning goals. Performance of concepts as social engagements is under-recognized as cognitive learning goals, since conceptual understandings are predominantly assessed and recognized through symbols and text. Procedural collaborations as a design, as well as an assessment mechanic for identifying learning events, is unique, as it invites us to design and look for players choosing to engage in a variety of ways as signs of understanding the relevance of different social engagements for different system goals. That is, instead of isolating a complex system experience to a single lens – constant competition in economic systems or full cooperation for ecological challenges – designing for learning through procedural collaborations pushes us to recognize the varying affordances of different social configurations, and helps learners learn how to transition between such configurations and to engage in the most appropriate ones for different situations. This learning and practice is also more authentic to most social and political systems in the real world – where creating cooperation across competing parties is a frequent requirement and a challenge people are often under equipped for.

Immersive multiplayer games are uniquely well situated to foster such a plurality of social configurations and help learners learn through them, as they support face-to-face interactions, and leverage the physical space to allow these interactions to happen at multiple points across the room (in some cases right on top of each other). In addition to the benefits of identifying emergent behaviors in complex systems commonly employed in physically collocated participatory simulations, games engage learners in role-play that makes their (interpersonal) engagement uniquely involved. Moving between different configurations like competitive goals to coordinated play, changes from being the creation of a system to learn from, to more deeply engaging as a city planner (or analogous) role wanting to succeed – either with or against others.

To this end, we investigated how *City Settlers*, a multiplayer city management game, could help learners experience and engage in rich and complex, collective world building, as they try to coordinate their actions over what are frequently competing resources and interests. To understand this, the research question driving our work were: 1) How can the design of (city) management games support the development of complex systems understandings? 2) How does negotiation and conversation within and across groups of player-learners reveal development in these understandings?

4.3. DESIGN

Designed to leverage the affordances of mixed reality, face-to-face learning of immersive and participatory simulations, *City Settlers* is a whole-room immersive simulation, in which the room "becomes" (through collective imagination, projected screens, and tablet computers) a fictional shared planet on which teams of participants develop their cities.

We designed *City Settlers* with interconnected mechanisms across specific city *metrics* (pollution, population, and happiness) and *resources* (gold, steel, cotton, and food) that depict each city's overall *stats*. These *metrics* are intended to allow teams to pursue different goals for their cities rather than one externally imposed goal state. The bidding and trading systems are designed to support teams to compete or collaborate as they see fit.

Buildings are acquired through the bidding mechanic – a blind auction system on a marketplace which generates random factories, farms, and parks to be acquired and used by the cities for their chosen goals (Figure 1). These are intended to be an adaptation of Antle et al.'s (2013) codependent access points – where teams are left unaware of others' bids, and a lack of coordination around information and strategies often leads to failed bids – which can remain a space for competition or become a space for coordinated action.

Player actions are distributed across three other screens. The "City status" screen (Figure 2), shared by the members of each team, provides information about the resources and buildings in a city, and the relationship between different resources and metrics. The "trade" screen (Figure 3.a.), available on players' individual devices, enables trading resources across teams. The "Planet status" screen (Figure 3.c.) is a large-format display at the front of the class (Figure 3.b.), providing information on the overall status of each city and the cities bordering it. Neighboring cities can affect each other by leaking excess pollution outside their borders, which provides another intersecting access point to incite players in working with or against each other.

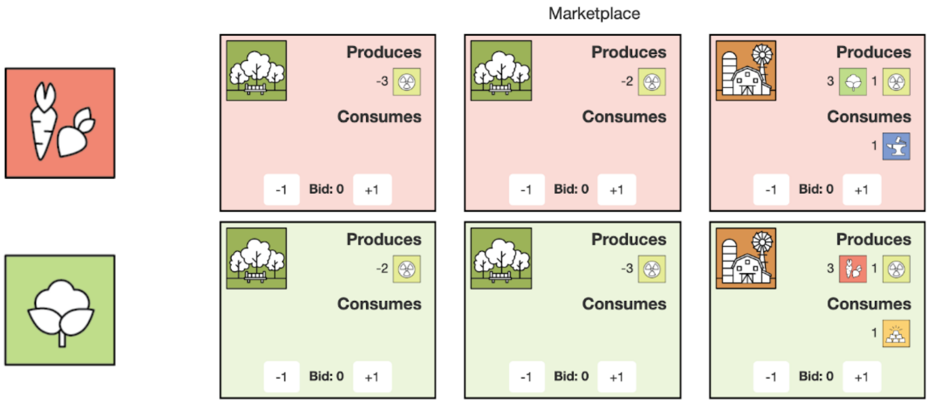


Figure 20. The bidding marketplace: the leftmost column depicts the resources used to bid on the buildings in their corresponding row - the first row being buildings that can be acquired by spending the *food resource*, and the second row can be acquired using the *cotton resource.* The first two buildings in both rows together depict 4 *parks* – which reduce the city's pollution when run. The right-most column has a cotton farm and a food farm, which use the products of *factories* to run (steel and gold respectively), producing food/cotton and pollution. *Factories* produce food or cotton, by using the products of farms. This view depicts the parks and factories that can be acquired by bidding food (first row), or cotton (second row). Cities do not know others' bids, and only the highest bidder on a building gets it. Bids that end in a tie "fail", in that no one gets the building, and it stays on the market.

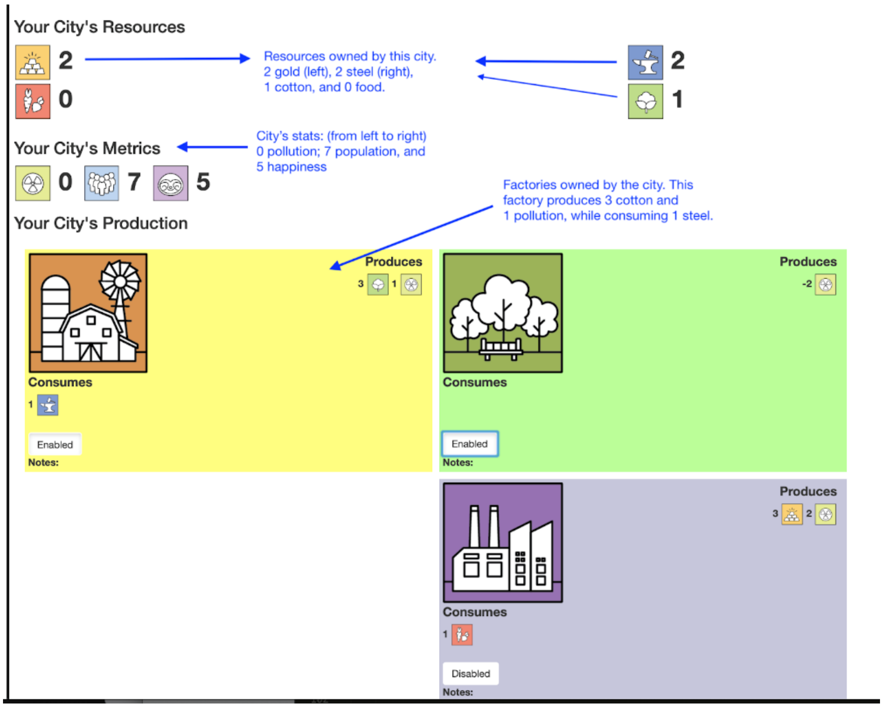
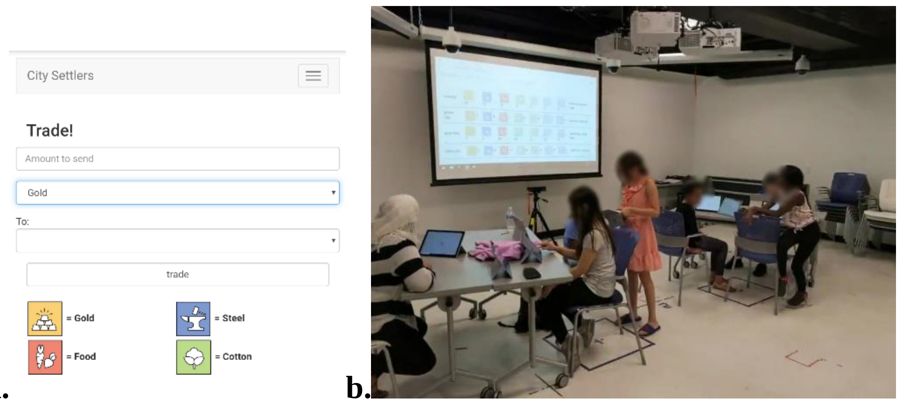
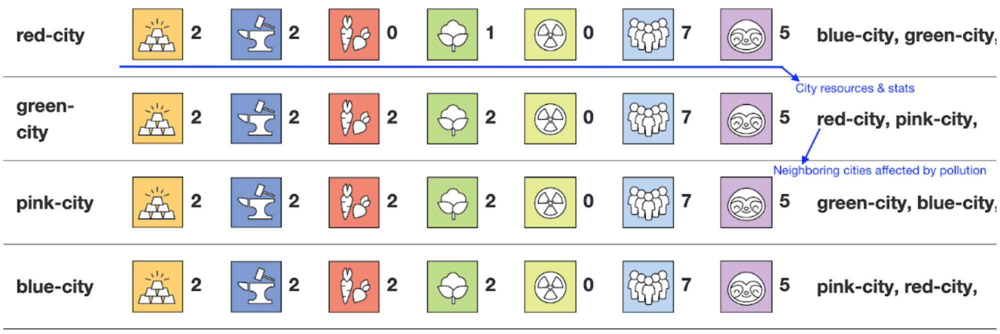


Figure 21. The city status view displays the resources that the city has. The city's metrics include pollution – which hurts population, as well as leaks onto other cities when it crosses a threshold; population, which is needed to run the different buildings, and is affected by the happiness and available food; and happiness, which is increased by a lack of pollution and availability of enough parks.



a. b.



c.

Figure 22. a. Screenshot of the mobile interface of person-to-person trading interface given to each player. This is intended to support collaboration

b. The game is played by teams of players with individual trading interfaces, the city and bidding view shared across their team on a common tablet, and a central shared display showing a "scoreboard" in

c. The scoreboard displays all cities' available resources, population, pollution, and happiness. This globally available information provides all the different kinds of information that players might choose as goals.

4.4. METHODS

Ten middle school students from a summer camp, in a mid-sized city in the midwestern United States, played City Settlers over 2 hours. Seven girls and three boys of different ethnicities were distributed randomly into four teams, introduced to the game, and asked to start playing. We did not run the camp and have little information on quantitative aspects of the camp. That said, we can describe basic impressions. The campers were familiar with all the devices being used (tablets, projectors, etc.) and were familiar with each other through their shared summer camp. All campers had some experience with games, though only 4 identified as “gamers”. The campers were provided food, and we read their presentation as middle- or upper-middle class. While not collecting demographic data from the learners, my observations provoke analysis on how race and gender might have mediated the creation of certain social configurations during this gameplay.

We collected gameplay data through telemetry, field notes and video recordings with the goal of identifying emerging and changing discourse (talk, gestures, as well as play actions) through multiple data modalities. The campers were invited to a technologically equipped classroom in a medium-sized city in the United States Midwest. This classroom had 5 cameras – one placed at the center of the ceiling recording a panorama of the whole class, and four cameras pointed four quadrants of the classroom (which corresponded with the four tables at which different teams were situated – Figure 23). We placed a portable microphone at each table to record conversations and synchronized the audio of each table’s mic with the corresponding video stream for eased video analysis. While our audio stream had a limitation of not fully capturing talk between students in the middle of the classroom away from any table, this rarely happened which we were able to confirm from our panoramic video stream. The teacher from the camp spent most of the gameplay sitting at a separate table away from most of the participation. Two researchers facilitated this gameplay, starting with a presentation explaining how to play, operating the game through its rounds while prompting the students to engage in different actions, and responding to students’ different queries.

In this work, we focus on presenting a case study (Merriam, 1988**)** of the learners' talk with each other and how it moves between competing over common interest purchases and coordinating across different purchases and complementary goals - reflecting different kinds of procedural collaborations. To reach these cases of different procedural collaborations, we began with a systematic coding process which drew from the Divergent Collaborative Learning Mechanisms Framework (DCLM – Tissenbaum et al., 2017), and Russ et al.'s (2008) framework on recognizing mechanistic reasoning. DCLM helped us highlight the different ways people interacted with each other – for instance by **narrating** their strategy, **modeling** different actions, or **negotiating goals** among each other. Additionally, we coupled DCLM frames with descriptions of within and across group codes – to surface contrasting patterns of interaction among teammates and across members of different groups/cities. Coupling this description of the collaborative modality with codes of mechanistic reasoning about the game (for instance, identifying **causal** relationships between **resources** and **population** change, or **predicting** the effect of running specific **buildings** and having different **resources** to gain **happiness** and other metrics) foregrounded developing understandings about the game, and the underlying system phenomena. These codes were applied at episodes characterized through a change of the involved participants. A long continuous interaction between two students would receive multiple codes enlisting all the different ways and topics about which they talked with each other. If another student came in, the episode as characterized by the group composition would change and be coded as a new interaction. The grouping of participants was done at the city level, so an episode of within-city talk would change when someone from another city would come in and interact with them. This coding work was done across three researchers who trained on select samples, reached adequate intercoder reliability, and coded the video across all four groups' video streams. This analysis surfaced broad patterns of how players interacted with each other across their gameplay and how these interactions changed over time, and in response to different game mechanics (i.e., system phenomena). We used our data analysis and this identification of patterns to pick cases which exemplified these different forms of collaboration in response to game understandings.

These collaborations are presented in chronological order, in a vignette style (Miles & Huberman, 1994) to provide a sense of temporality and progression between the different kinds of collaborations, and how they built on top of each other. The description of the whole coding system and the specific codes are outside the scope of this study. To deeply understand these interactions, I present these conversational excerpts paired with a discussion about the system phenomenon understanding reflected in the interaction, and how the design of the game and setting effected these interactions (i.e., an expanded explanation of what our codes compactly represented). This talk and analysis are coupled with highlighting the movement of players across the classroom's physical space. This was drawn from the adding thicker description to the codes we had already applied to the interactions (for instance, for interactions coded as **across group** talk between two teams, we added a description of which table the interaction took place at and which specific students were participating).

Lastly, we couple these analyses with a summative description of gameplay actions that took place between groups. We collected telemetry data of students' gameplay on the same server that maintained the entire game state and responded to players' actions. The City Settlers server (situated on the university's AWS servers) is where we host the game, lead all players to register, login and play on, and which records the different actions that players take, records the corresponding changes in the game state and reflects this game state data to the players to think about. The most overt across-group interaction in the gameplay data was reflected in the trading of resources between cities (conducted by individual players on their mobile interfaces, and not the city level shared tablets). We present a plot of which cities traded resources with each other to point out patterns of the interconnectedness between cities' collaborations and how that intersected with the different participatory behaviors and patterns exhibited by the groups of players.

We present these changing collaborative interactions as a result of the game's features centering flexibility across forms of play and engagement, and how the evolution of learners' interactions represents a development of understanding. These understandings are reflected in the goals they choose and the strategies they attempt through inter-player talk, negotiations, and in-game actions.

4.5. RESULTS

Initially, gameplay began with players attempting to acquire buildings from the marketplace. This is evident in the composition of within group as well as across group conversations – they largely center around what buildings the teams want to buy and how much they want to bid on them (Table 1).

Table 1

(Bidding Marketplace)

Competitive or "Parallel" interactions aimed at striving for individual growth – acquiring capital (resources or buildings) by bridging information gaps – and only coordinating pursuits in the short term (asking for other teams to not bid on a building; offering them an alternative option that would help both teams, but not incur any cost on the proposer).

Speaker-Group	Dialogue
Nikhil – Red City	"Are you bidding for the cotton park?" (referring to the park that is to be purchased using cotton)
Beth – Green City	"Can you let us have the steel factory? You can have the cotton one instead."

This is a direct consequence of the design of the game – where starting one's economy and actions in a city relies on acquiring buildings, which in turn are obtained through a scarcity driven market. This is resonant with basic models of economic development, which describe an initial direction at producing resources to enable participation in broader economies, and gradual cognizance of broader social systems affected by the economy (Stern, 2004).

Once players' cities began to develop (e.g., producing or acquiring most of the resource types), teams expanded their goals beyond having access to resources. Since a city's population limited the number of buildings it can run, and access to different resources affected population and happiness, teams started paying attention to the other changing metrics of their city. This led to an increase in players attempting to understand how these metrics work. Players also started articulating and grasping more complex causal relationships in the game in order to aim for specific goals (Table 2).

Table 2

(City Display)

Competitive or "Parallel" interactions aimed around individual growth, and negligible goal or strategy coordination across teams

Episode	Speaker-Group	Dialogue
1	Eric – Red City	(Reading off the screen) We do not have population, cause the food is more than population, people are

		well fed, and the population increases; if it's less than 0.7x it drops, so we can't have population
2	Eric – Red City	How much pollution do we have? We have 7 pollution?! What?! We have so much pollution!
	Nikhil – Red City	We have minus people, we need food
3	Eric – Red City	We need to turn off one of your factories to run our park… Now I get it

This provides an example of a "need based" inquiry into the game's underlying economic systems, which involves producing resources that are specific to sustaining social systems. Here, players engage in inquiry aimed at **barriers to growth**. This growth was not just in terms of increasing resources, but also aimed at reducing pollution. It was evident to them that their rising pollution was affecting them as well as others (Table 3).

Here, the push towards competitive orientation – with groups comparing their relative populations to those of other cities – was facilitated by the scoreboard presented on a separate large central display. This display was intentionally designed to require all students to use the same centrally located information space to unpack macro-level (i.e., whole simulation) game states. As a result, the display afforded unique opportunities for students to engage in shared expressions of the state of the game, with students shouting out how their city was doing to the rest of the class, and in many cases comparing different success metrics between the cities. For instance, right before Table 4's episode 2, Pink City's members had public (distressed) inquiries regarding "Who is polluting us? Who is spreading pollution?" This led to a public conversation across Red, Green, and Pink City where they found out that both Red and Green city were spreading pollution.

Table 3

(Central Scoreboard)

Recognition of damage caused by industrial "development" – locally and globally (in terms of cities)

Speaker-Group	Dialogue
Nikhil – Red City	"Make everybody's lives miserable, even our own people!" (this was said both in humor as well as despair, as it was followed by "Why am I so happy?!")

As mentioned above, a key aspect of immersive participatory simulations is the ability for physically situated phenomena to affect other elements in close proximity. In *City Settlers*, one of the ways this was achieved was through the spread of pollution. If a city's pollution rose above a specific threshold, their pollution would spread and start to negatively impact the cities closest to them. This could in turn have cascading effects, causing the pollution in those cities to rise, and eventually spreading to even more distant cities. The spread of pollution from one city to others led to the creation of complex inter-team collaborations (Table 4).

Table 4

(City View)

Recognizing the interconnectedness of cities, and moving from understanding, to demanding others independently change their actions (independent or competitive participation), to eventually negotiating exchanges which enable mutually beneficial pathways for growth (positive coordination)

Episode	Speaker-Group	Dialogue
1	Neha – Blue City	Can other cities' pollution affect us?
	Researcher/ Facilitator	Yes, they can.
	Neha – Blue City	How is that fair? What should we do?
	Researcher/ Facilitator	You need to talk to red city and see if they can reduce their pollution"
2	Pooja – Pink City	Green city! Stop it! Stop polluting us! You need a

		park! We need a park!
	Beth – Green City	If you don't bid on the park that has cotton, we can give you… (Speaking to Pink City)
	Pooja – Pink City	If we try to get a park, then they will not get a park. We can ask for steel so they can get a park… (Discussing within her own Pink City group)
	Nadia – Pink City	You better get a park! (directed at Green City)
3	Beth – Green City	We don't have enough people
	Amy – Pink City	Which park are you doing?
	Beth – Green City	Wait no no no, we're not bidding for a park, literally, we don't have enough people to run them. We have two parks right now. If you give us food, then we… If you give us food for free, then we won't pollute your land
	Nadia – Pink City	Why for free? You should give us something. We

	give you food then you give us
Beth – Green City	No that's not; I mean if people aren't there...

This negative feedback loop across teams – one team's pollution causing negative effects to their physically proximal peers in the class – was designed to be a driver for inter-group communication. Being negatively interdependent is an integral factor in the real-world phenomenon of sustainable development; as well as a mechanic that pushes for players to have to discuss and negotiate with each other directly. We expected this mechanic to increase the occurrence of players physically *moving* to others' "cities". This was reflected in the implementation, where after multiple rounds of pollution growth, it began to spread from Green and Red City to their neighbors. When this happened, Beth from Green City moved to Pink City's table for an extended period of time, with Beth and Pink City's members discussing the impacts their cities were having on each other and the system as a whole (Table 5).

Table 5

(City View)

Mutually beneficial coordination developing into cross-team strategization and collaboration

Speaker-Group	Dialogue
Pooja – Pink City	Get a park, you're polluting us (as Beth comes over to Pink City)
Beth – Green City	I know
Pooja – Pink City	You aren't just polluting us; we're polluting you guys
Nadia – Pink City	Wait, who's polluting us?
Amy – Pink City	Green city
Beth – Green City	And blue city
Amy – Pink City	Blue city's polluting us?
Pooja – Pink City	No, we're polluting them [...]
Amy – Pink City	Our happiness is so low!
Beth – Red City	So, what do you need for that? (Scrolling through their City Interface and looking at their marketplace bids) Yeah 4 steel. You need steel, let me see how much steel we have.

Most cities managed to overcome the problem of over-pollution by working together (different teams engaging in different amounts of involved collaboration), and eventually went back to individualistic pursuits stemming from trying to improve metrics (independently – ”our pollution is so low now!”) or perform better in comparison to other cities (“[...] we have 3 people. [...] Pink City has 9 people!”) (Table 6).

Table 6

(Central Scoreboard)

Individual pursuits on newer goals chosen after having overcome inter-city conflicts and challenges

Episode	Speaker-Group	Dialogue
1	Neha – Blue City	Yeaah! and we have 0 pollution and 3 people. Oh my god, pink city has 9 people
2	Eric – Red City	Yes! Our pollution is so low now!
3	Nadia – Pink City	Yay! We got happiness!

Adding to the central theses of this paper, a “form of collaboration” not directly under the fold of learning through collaboration is when it doesn’t work. Often group work involves failure of coordination and participation in a variety of ways that leads to inequitable learning gains, and different forms of marginalization

(Barron, 2003; Miller, 2006). Marginalization through social markers (like race, gender, socioeconomic status, etc.) often intersect and overlap with other classroom marginalizations reinforcing knowledge gaps, lack of community and peer support, and seeing oneself as a (potential) competent practitioner or expert in a discipline. In our gameplay pilot, we were able to notice striking instances of disengagement from teamwork and gameplay, especially as a result of specific behaviors from their teammates. Here I present short accounts of how this gameplay involved two situations where certain players were left out of any significant gameplay. Since these accounts were marked by a *lack* of communication, these descriptions are not described as systematically as the other instances, but are left as situations warranting further exploration, and better design practices.

While we did not collect demographic data around ethnicity from the players, we identified green city's two members as Beth and Rachel, a white girl and a girl of color (likely black) respectively. Noticeably through our highlighted episodes, and through the remaining data as well, Rachel almost never engaged with any other player of the game. Beth had established familiarity with the interface and control over the game early on, and very soon Rachel was rather reserved for most of the gameplay. Towards the latter half of the game, when members of other teams were coming over to Green City's table frequently, Beth occasionally asked Rachel to engage in some trades, and complete some actions. While this appeared like instances of apprenticeship – where Beth invited Rachel to engage in simple actions, recognizing that she was not participating for the most part – the lack of designed opportunity or affordance for Rachel to contribute in a way novel for Beth appeared to be a significant challenge in seeing her participate more.

Red City comprised of three members – Nikhil (an Indian boy), Eric (an Asian boy), and Emma (a white girl). Emma began sitting across from Nikhil and Eric and ended up not getting up from her position for most of the game. This was in contrast with both Nikhil and Eric who spent a majority of the game moving around, with the city view tablet in their hands. The portability of this shared view played strongly against Emma being able to participate – for much of the game she was not able to follow city specific status information except when her teammates would inform her of changes. A few times she tried to engage with Nikhil and Eric by asking about decisions, and their changing understanding of the system, but she was visibly left out from participating in the gameplay in the forms they took up.

The face-to-face nature of the immersive simulation played a key role in these interactions, with most of interactions taking place in a fly-by manner – with players visiting other teams' tables and only pausing long enough to receive an acceptance or rejection of their proposal. This was characterized by exchanges shorter than 3-4 turns and lasting less than 30 seconds. These interactions also engendered the creation of mover-sitter roles – some players who did a majority of the moving around, and others who never moved from their table (Figure 4). While Red and Blue City had active movers, Pink and Green City had completely stationary members and occasional movers. Pooja & Amy from Pink City only went to Green and Red City tables, less than 5 times in total; and Beth from Green City only went to Red City twice, located immediately next to their table, and to Pink City 4 times, located across from them. Figure 4 depicts the distribution of players across the room, and a highlight of the movements by different players. The grey highlights players who never moved from their table. A recurring factor among the non-mover players included limited access to the City tablets, which other members in the team were tending to control and carry with them while moving.

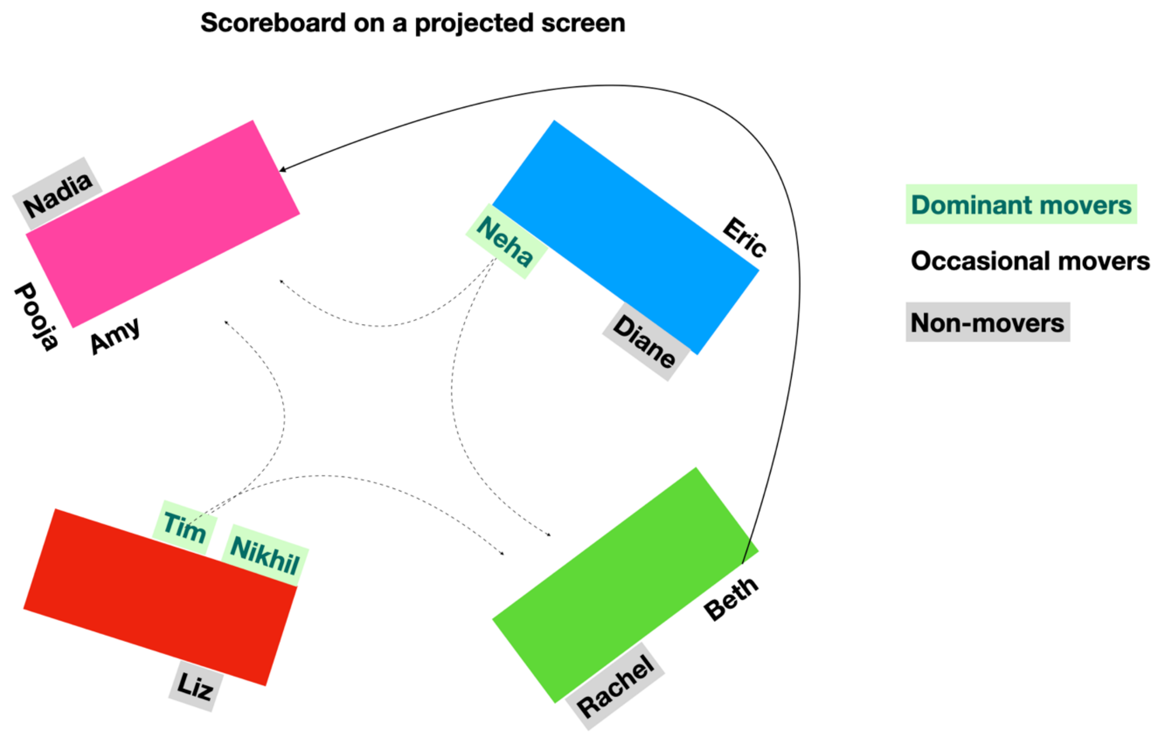


Figure 23. Positioning of the different cities' tables and players over the room. The players highlighted in green are the most common movers, who mostly only visited Pink and Green City. Pooja, Amy, and Beth were occasional movers, with Beth going across to Pink City for an extended period of time (discussed more in

Table 5). The names highlighted in green are the *dominant movers* (moving through most of their gameplay and conversing at others' tables); and the grey highlights are players who never left their table.

A glimpse of the inter-city connections enabled by these different movement performances is depicted in Figure 5, which presents which teams conducted trades with each other – pink and green city traded with all other cities, and red and blue never traded with each other. This is particularly remarkable since Red and Blue City had dominant movers, and Pink and Green City's members were much more limited and deliberate in their movements across tables.

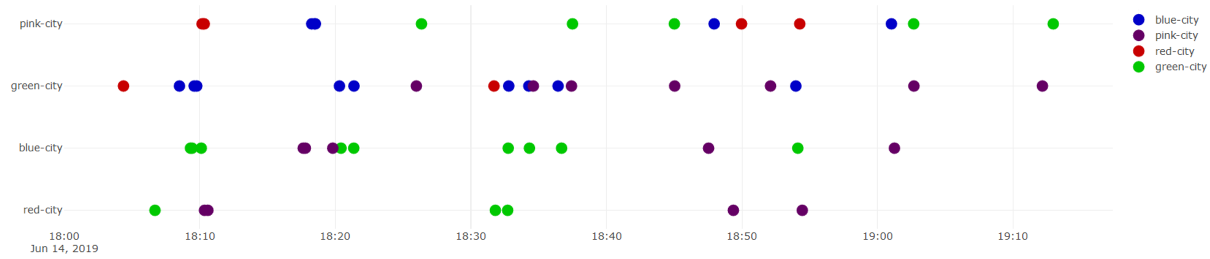


Figure 24. A plot of which cities traded with other cities across the gameplay session. A key highlight here is how blue city and red city never traded with each other, only with pink and green city, whereas pink and green city had trades with all other teams.

4.6. DISCUSSION

This paper examined a spectrum of collaborations that took place within and across teams while situated in a whole-class participatory simulation, and how these collaborations resulted in changes in students' domain understandings, goals, and strategies, both within and across groups. In the context of sustainability education, these collaborations serve as means for students to develop the kinds of interdisciplinary and interconnected reasoning required to understand such a complex topic. This system level understanding, both as a collaborative act and as a central learning goal sits at the heart of what we call *procedural collaboration*. Focusing on procedural collaboration enables us to inspect the value of in-game interactions as conceptual understandings themselves.

As students took part in *City Settlers*, they needed to work with their group members and the other cities (groups) to navigate and understand how their collective decisions impacted both the micro (city level) and macro (whole class) system phenomena. While early decisions in the game were largely prescribed - such as students bidding on and buying their first building (Table 1 above) - how the simulation would unfold became increasingly unknown and driven by the groups' decisions and collaborations. As discussed above, many of these decisions were made on-the-fly as students moved around the room and made plans based on their awareness of what other teams were doing, and their ability to coordinate trades and bids (avoiding competing with other cities or using their awareness of what others were doing to overbid them).

The blind auction system was a particularly interesting competitive mechanic, with the highest bid winning each time. It was intentionally designed to create information gaps between groups, by not showing each city how much others were bidding. This created space for more cooperative actions, such as cities coordinating what to bid, or not bid, for. This enabled cities that worked in this way to spend fewer resources on pursuing specific buildings and strategies, as was seen in the negotiations between groups in Table 1.

Similarly, students moving around the room and getting information from other groups, fostered competitive and collaborative orientations. As we saw in the case in Table 4, pollution spread caused Red City to identify which cities were the key polluters, and to push them (specifically Green City) to do better! This eventually became a deeply cooperative set of mutually beneficial moves (Table 5), where they pursued mutually exclusive buildings and set the stage for supporting each other as allies. The students' development of deeper understandings of the system and their underlying processes, resulted in complex collaborative strategies. This kind of collaborative understanding and negotiation of desired outcomes stands in contrast to many traditional classroom learning experiences wherein individual students (or groups) focus on “states” as markers of progress, and what they need to outperform their peers in. This narrow focus in turn limits space for divergent, or parallel goals.

Building on this, the cases shown in Tables 4 and 5 highlight the complex interactions that groups developed in response to their growing understanding of the underlying interdependence within the simulation. Once they realized that pollution could spread across the physical layout of the classroom, they began to adjust their strategies and goals towards more parallel and less competitive orientations that allowed their respective cities to best succeed. In Table 4, we see teams extending pressure to the polluting cities and responding with efforts to coordinate. Exchanging resources as a way of coordinating actions on the marketplace, as well as running different sets of buildings was a unique negotiation that emerged out of the deeply interconnected systems within and across the cities. This coordination between Green and Pink city became more involved, where in the next round, Beth from Green city actively interacted with Pink city's bidding interface to figure out how to trade resources appropriate to get parks for both teams (Table 5). This was a particularly powerful shift in students' orientation on their goals, from being purely competitive (i.e., *us* against *everyone*) towards an understanding that in order to succeed, they would need to work with others to maximize their own growth (and reduce negative system-level effects).

These cross group procedural collaborations did not mean that groups were unable, nor dissuaded, from diverging from the collective goals to orient towards their own micro-level goals once the macro-level issues were satisfied. As Table 6 shows, at the beginning of each round, students still were deeply concerned with how their individual cities performed, and largely made decisions that aimed to improve what they identified as the key metrics for themselves, and how it related (competitively) to other cities in the room. For instance, while Pink city succeeded in raising its happiness, and Blue and Red cities celebrated their low pollution, Blue city lamented their lower population in comparison to Pink city (which, however, had much higher pollution than them).

We also observed how the technological design decisions concerning which interfaces and devices carried which pieces of information, played key roles in facilitating the procedural collaboration. Using tablets for the team interface was intended to provide a medium sized display that could be seen by team members around a table. An unintended effect of not tethering the tablets to their corresponding tables, was that the *movers* often decided to carry the team tablet around with them while engaging with other teams. This often left the stationary (*non-mover*) team members to be left with a lack of information to process (buildings on the marketplace; state of the city and which buildings to run or not) and decision-making power. Despite the stark difference between the *dominant mover* and *non-mover* roles, the space-oriented and multi-interface supported gameplay afforded contribution across roles. This was made evident by how the trade connectivity (i.e., the number of teams they traded resources with) of teams which had dominant movers was less than that of the teams with moderate movers. We also saw some non-movers engage in public as well as cross team talk and strategizing – specifically Nadia from Pink City in Table 4 and 5 contributed to in-team strategizing as well as engaging in negotiations with Green City.

There are other possible explanations for the limits of trade connectivity from the movers. We observed from Table 1, and other observations, that Red and Green city members did interact, occasionally engaging in quite complex negotiations. Understanding the learning experiences of different roles in such environments is a much needed space of inquiry since research around emergent roles often raises the concern of providing variegated learning gains across different learners (Strijbos & Weinberger, 2010). While some non-movers did participate in this gameplay, others (specifically Rachel from Green City, Liz from Red City, and Diane from Blue City) did not at all. This lack of participation is often a gameplay challenge in learning environments and needs thoughtful design to make space for productive engagement across more players. We are currently exploring different possible design solutions to mitigate the non-participation of players. These include the introduction of limited scripted roles, so different players have unique abilities and responsibilities creating motivation as well as space for broader participation. We also saw the negative consequence of portable city interfaces – wherein *mover* players carried the tablets away leaving their other teammates with a lack of control over or critical information about their city. This informs us of the value of constraining portability over some interfaces (specifically small group displays in the case of City Settlers).

We acknowledge some limitations to the work presented here. The short duration of our data collection – testing gameplay over one afternoon with learners from a summer camp – limited our understanding of the long-term educational value of such activities. It is likely that extended play and embedding in a classroom curriculum would lead to players engaging in social configurations around the game differently (Lee & Probert, 2010). Relatedly, this study did not collect demographics data or more detailed data about students' pre-existing relationships with each other. While we know that most of the students had come from different schools to the summer camp and did not know each other apart from the last 3 weeks, learners' common styles of interpersonal engagement across a variety of environments, and learners' prior preferences (of comfort or discomfort with respect to each other) play integral factors in conducting and experiencing successful gameplay and learning experiences (Tolmie, et al., 2010).

4.7. CONCLUSIONS

Designing for and assessing learning activities in ways that explicitly aim to support *procedural collaboration* expands the ways productive learning is conceptualized and subsequently enacted. By being able to design systems that support a wide variety of collaborative interactions – from building their separate cities, competing on a marketplace, collaborating for individual or collective gain through resource trading – in an authentic deeply interconnected system, we were able to support learners organically engaging in the collaborative coordinations that were required for them to achieve their micro and macro goals, and in the process, understand the overall system. This builds on work by Pellicone et al. (2018) collaborative digital games, in which the design of a social museum game enabled the concepts of parallelism and agent-based modeling to be reflected in how learners divided tasks and acted on a shared artifact. These diverse need-driven social configurations afford unique access to agent-perspective-based learning. In these interactive and participatory spaces, learners are embedded in perspectives where they develop different understandings, priorities and strategies in the system, and contribute to each other's' learning in richly contextualized ways. The pursuit of sustainability is an emergent complex phenomenon and features unique multiple-agent relationships that are unique to each instantiation, both in the real world and in each playthrough of *City Settlers*. This authenticity creates space for learners to develop richer and novel ways of thinking about complex systems, and practices of negotiation and collaboration which enable them to meaningfully act on and within them.

The examples of diverse collaborative interactions in different social games adds to the work on divergent and emergent collaborations (Tissenbaum et al., 2017; Halverson et al., 2019) which demonstrate how environments designed to enable different forms of collaboration, see learners fluidly move across modalities which afford them learning opportunities most appropriate for their preferences and needs. DeLiema et al. (2019) also demonstrate how a classroom game developed to support a diversity of social configurations afford multiple entry points into complex science inquiry. In *City Settlers*, we find traditional forms of learning through on-screen text and access to the "teacher in the environment who was around to give answers. More uniquely, they experientially uncover phenomena in the world as they took place (the challenges of a starving population shortage; or the spread of pollution to outside one's city), and deal with these by creating different forms of coordinated activity across each other – ranging from trading resources to helping each other acquire buildings in mutually beneficial manners.

This work also shows the role that augmented and immersive spaces, and participatory simulations in particular, can play in supporting these collaborative and competitive interactions. Transforming the physical classroom into the simulation itself places the students directly into the learning, enabling them to *live* the phenomena as it emerges. Further, by creating augmented spaces in which the physical environment of the classroom and the digital representations of the simulation and devices work in concert to immerse the learners in the content (Klopfer & Squire, 2008), enables us to transform the classroom from a passive medium to a driver of collaboration and sensemaking.

While this work surfaces a wide array of social learning phenomena and procedural collaborations that emerge in immersive whole-class simulations, studies across different populations, contexts, time durations, and curricula are integral in deeply understanding how these engagements could help and also possibly hinder learning. In response, we are currently working with teachers in history classrooms, science classrooms, and longer duration summer camps to develop versions of *City Settlers* which complement different curricula and learning contexts. Our goal is for this extended research to highlight a variety of procedural collaborations valuable in different domains, the cross disciplinary nature of learning accessed through many procedural collaborations, and also develop design examples for how such social learning simulations can be modified and used across different curricula.

Chapter 5: Discussion

The premise of designing for greater learner agency in collaborative spaces in my work centers sociocultural perspectives on learning where learning is fundamentally a social act where learners develop and practice skills in relation to others in the space. Thus, a critical form of learning involves learners becoming practitioners of personally and socially authentic tasks. Centering this authenticity allows learners to both engage with ideas in ways they find engaging and do so alongside others in ways that enable them to form relationships and develop communities of learning – spaces where they grow through teaching as well as learning from others.

Much work on authenticity focuses on the relationship between learners and the task, but a critical aspect includes developing authentic and productive relationships between the learners. While this has been studied, described, and designed for in persistent spaces across different conceptions like communities of practice (Lave, 1991) and communities of learners (Rogoff, 1994), understanding and supporting a diverse set of social configurations is underexplored in many informal learning environments.

Learning across different social configurations (i.e., learning as a mentor, collaborator, competitor), even around the same domain enables deeper understandings. This is especially evident in City Settlers where enacting competition of interests across complex interdependent entities like cities enables access to understanding real world negotiations and the different political resolutions chosen by decision makers. This learning is uniquely more powerful than common forms of education around these domains. For example, engaging with these dynamics as theoretical models is far more limited in how it expands ways of thinking about the domain as well as different social configurations (i.e., interpersonal relationships) (Frank et al., 1993). Similarly learning experience and opportunities afforded during peer teaching experiences are particularly valuable, since they have closer access to learners' ZPD (Vygotsky, 1962), and also contribute to identity development of expertise and community belonging among other aspects.

Creating space for engaging with each other in a diversity of ways is also critical for personal and cultural relevance. Learning environments (like all environments) carry social histories and politics of their own design as well as the learners. Constraining the ways learners choose to work with each other limits their ability to interact with each other in fuller and more personally preferred and relevant manners. For instance, gendered and racialized dynamics in classrooms (among other environments) affect how comfortable learners feel with their teammates and others in expressing themselves (Swenson & Strough, 2008). Forcing them to cooperate with people has identified negative impacts on learning, and it is necessary to integrate space in learning environments for learners to not have to work with this discomfort in forced and unproductive manners (Beigpourian & Ohland, 2019).

The studies in this dissertation focus on ways to design spaces in ways that enable learners to socially engage in a variety of ways. To synthesize my analyses across the three studies into common design patterns that varied across the projects and shed light on ways these patterns affect collaborative interactions, I use Conjecture Mapping an analytical framework used to analyze system designs for their impact on learning, to identify central design pillars across the learning environments in my studies. In Conjecture Mapping, the embodiment of a learning system is described as consisting of **(1) Tools and Materials**, **(2) Task Structures**, **(3) Participant Structures**, and **(4) Discursive Practices**.

In the studies in this thesis, these categories inform the selection of 3 specific factors that vary across the environments and are key in affecting the collaborative interactions fostered in each space. These chosen design factors are:

- **Task Modularity** (relating to (2) Task Structures);
- **Peer Awareness** (relating to scaffolds for (3) participant interaction and (4) discursive practices, in terms of the ways these interactions are initiated and conducted); and
- **Individualized Feedback** (belonging to the intersection of (2) task structures and (3) participant structures).

This analysis positions a distinction between designed tools, and practices and social relationships between people. I do this to be able to present more applicable design recommendations in synthesizing my work across these studies. This approach does not fully use many possible post humanist lenses to analyzing collaborative learning (Peppler et al., 2019). While Chapter 2 presented an example of how considering the space of the classroom, the positioning of different screens and interfaces related to the Connected Spaces tools acted as mediators and agents in crafting what were approachable modes of collaboration, the discussion here does not give the same agentic role to the designed tools. My future analyses and work are more deeply engaging with how we can talk through design hypotheses while recognizing the agentic, cognitive, and cultural roles played by designed tools and their features.

In the rest of this section, I delve into each of these design features and how the earlier studies in this thesis tell us of their effects on fostering different kinds of collaborative interactions. After explaining what these features specifically mean, I present a table that summarizes the effect of different "levels" of that feature on the kinds of collaborative interactions it fosters. The text in the subsection then presents the details of these connections and how they are supported through the cases and data discussed in the studies, largely expanding on and explaining the summary presented in the table.

5.1. TASK MODULARITY

Collaborative work often involves a complex activity that is composed of subtasks. This is most noticeable in an old, commonly designed collaborative learning activity called Jigsaw learning, where the subtasks are given to smaller groups or individuals. After some amount of working separately, learners come together in larger groups to synthesize their learning/work. As discussed in the introduction, researchers like Roschelle (1992), and Roger & Johnson (1994) count the coordinated work when learners come together as collaborative learning and demarcate the period of separate work as cooperative learning. Here I describe those different periods as changes on the axis of *goal orientation* among learners engaging collaboratively. It is valuable to count both phases as parts of the broader collaborative learning experience especially in the studies of this thesis, since moving across goal orientations is often voluntarily chosen by learners and is often a result of their own choices and actions.

The example of Jigsaw activities presents a clear example over how access to the modules of tasks – subcomponents that fit together to make up the broader activity, can make (or constrain) space for accessing different kinds of social configurations or collaborative interactions in a learning environment. Here, I describe task modularity as a design pattern which refers to (an increased) modularization in terms of the number of different subtasks learners can engage with, as well as the different ways these modules can be put together to enable different kinds of success or completion. As reflected in the studies in this thesis, open ended learning environments are often characterized by the ability for learners to choose from different goals for themselves. This is rarely possible without activities being complex, which in turn is both supported and made possible by modularity.

Related to maximizing towards the open-ended nature of our learning environments, we have also tended to use the modular subtasks to often represent different optional subgoals. This involves two different aspects – some indicators of complex success should be accessible without engaging in every subtask, and relatedly learners should be able to switch between subtasks in response to their preferences/current understanding. These features contribute towards what makes the design of an activity *more* modular.

Modularity is a useful design pattern in representing many real-world complex tasks in an authentic manner. Most large projects we do as professionals often have goals that we can adjust to varying extents, and our goal choice is affected by and informs the subtasks we choose to do. The number of ways we can complete a complex activity is often infinite, and different sets of subtasks enable accessing the goals we choose for ourselves. As with any environment of learning or practice, constraints on these choices enable channeling successful and deliberate growth towards productive directions.

Modularity is best utilized when it fosters accessing understandings through multiple representations. Multiple ways of approaching and using a skill allow for deeper understanding and learning (Ainsworth, 1999). This does not mean that every learning environment should have numerous ways of doing the same thing, but that the design of learning environments and their underlying tasks should center access to a skill in novel ways, rather than reinforcing a fixed/narrow set of representations.

In the following table, I describe how engaging with different levels of task modularity fosters different kinds of collaborative interactions among learners, in particular across the studies in this thesis. I use the three grouped features of collaborative interactions as discussed in the Introduction: Goal Orientation, Role Taking, and Negotiations, to describe the changes in nature of collaboration at these different levels. The table is followed by more detailed mappings and discussion between the different design levels and the specific instances from the studies in this thesis.

Table 6. Different levels of Modularity and its impact on different features of collaborative

interactions

Level	Goal Orientation	Role taking	Negotiations
High	Learners often end up in siloes of isolated subtasks, leading to limited social interaction.		
	Goal orientation (competition or coordination) becomes distal – actions are too siloed and less motivated/understood at system level. This often becomes or looks like parallel play.	Roles are often disconnected and only rarely interact. So, roles are created from prior interactions and often sustain.	Limited social interaction leads to/equals minimal negotiation!
Medium	People can choose to compete or coordinate as they move through different parts of the activity; competing when they choose to do similar subtasks or coordinating when doing	Learners are able to work with different folks across diverse expertises, depending on the subtasks they engage with.	People can choose to do separate things or coordinated things.

	complementary things.		
Low	Sense of competition often takes over when everyone's doing very similar tasks. Otherwise, it leads to parallel play where different players are doing the same thing	Individuals can become drivers/teachers; establish power/dominant roles constraining others' experience.	There is often serialization of subtasks (doing things one after the other) or doing the same thing in (parallel) competing with each other.

5.1.1. High modularity

The Connected Spaces activity with App inventor had overtly high modularity. Making (applications) creates space for a countless number of approaches to solve problems, App Inventor (and many other tools) also offer many preexisting templates and examples for makers to integrate into their solution; and there is also space for makers to constantly reformulate their design to use problem solving methods they are more familiar with. This is richly productive for learners to engage with agency, focusing on skills and approaches they find most (personally) meaningful.

When modularity is high, integrating 'help' - bridging different actions or bodies of knowledge - becomes harder. More expertise is needed to understand components that can be integrated productively. For instance, in our App Inventor activity, people who wanted to build a map functionality in their app were struggling to understand how to provide better feedback to their app's users. To understand that they needed to know how to use the network module and image modules, required knowing about the platform broadly, the underlying vocabulary for different modules, and also how to locate the required help (online or amongst each other). As described in our case, this was solved through teacher/expert intervention who could formulate their challenge as composed of specific sub tasks, and which other students in the classroom would be productive collaborators.

In Rainbow Agents, when players didn't know how to synthesize their disparate understandings, they just played in parallel. This is particularly noticeable in how participants who did not know each other found/created moments of negotiation and connection – often about knowing different game mechanics or understandings about the game status – and sharing that with each other. We know from work in museum exhibits that productive participation at museum exhibits flourishes when there are opportunities for social connection, which successfully takes place when other designed affordances align (in particular, awareness interfaces about peer knowledge and awareness) (Tissenbaum, 2020).

This lack of active social interaction leads to not much variability across any possible collaborative behaviors – goals and relative status does not change, as there are negligible opportunities to engage or negotiate around the same.

5.1.2. Medium/Balanced modularity

When subcomponents work well – that is, learners know how to synthesize different understandings or skills to further their progress – many productive social configurations occur. The case from Rainbow Agents, where the boys in case 1, who start as competitors, entering with authority over the space, quickly realized the value of asking each other for help and sharing understandings. This was exemplary of a quick change over how the players **related to each other** in this space, and also an **evolution of their goals** (from "defeating" the other group, to understanding/"winning" the game). So instances of negotiation over in-game goals as well as pursuits relative to each other were made possible as appropriate levels of modularity were achieved. As discussed in the case, the other key affordances – peer awareness as well as space for individual work – played key roles in enabling this level of appropriate modularity.

In Connected Spaces, as discussed above, opportunities to bridge high modularity were also created through expert support – wherein teachers were able to exercise their understanding of the domain i.e., how to solve problems, as well as their awareness of different students' expertises, to facilitate social connections and peer learning opportunities. Since these brokered events were regulated, there were rarely any observed moments of negotiation around goals and relative roles – there tended to be a clear helper-helpee exchange of information.

In City Settlers, learner understanding of the different subcomponents of the system and their connections was exhibited when they started making cross game-mechanic deals, i.e., planning trades in exchange for different bids in the game. This was a complex alliance since it did not violate a broader competitive orientation in their play but created temporary moments of cooperation (changed **goal orientation**) and often involved newer **interpersonal roles** (giving advice, sharing strategies, and so on).

In Rainbow Agents, the design itself provided events of "assembling" work across different modules/components into productive outputs. Often thunderstorms would occur (that is, adequate biodiversity across the garden achieved) even when players were working on different aspects of the system – for instance, just trying to open treasures, trying to make some plants survive, just tinkering to understand how the different agents work. Similarly, in City Settlers, the inter-city pollution mechanic, which spread excessive pollution to neighboring cities, created instances of different task components and learners' goal pursuits intersecting to invite investigation into how participants could work together. This was intended to create opportunities to identify bridge-able gaps in modularity, further discussed in the **awareness** section.

5.1.3. Low modularity

In activities with low task modularity – tasks which can all be done by the same person, or have a forced serialized order for completion/success – there is often a creation of relative expertise and **dominant/driver roles** in some learners who often take over a bulk of the activity. This relative expertise develops through a variety of mechanisms. Learners who are around in an environment long enough (relative to its complexity) will eventually have enough knowledge to understand most parts of the system and possibly encroach others' exploration experiences. We see this in the second Rainbow Agents case where the boy who had been around for an extended duration initially resists negotiation from the newcomer kids for picking goals or doing specific actions. His offered suggestions to others tended to be with authority and didactic and had to be resisted by the kids for them to pursue their own interests in the space. Low modularity of the system was not the only or primary cause of this interaction. The tendency to take driver roles comes up in many other situations – most notably toxic when it reinforces recurring social structures and tendencies akin to men overlooking women's contributions in the workplace and often unwarrantedly assuming seniority or expertise over them (Schiffrin-Sands, 2020). At the same time, spaces with a constrained set of tasks increases the likelihood of occurrences – if a learner has engaged with a system to gain familiarity, they are likely to overestimate their own expertise (Kruger & Dunning, 1999), and might engage in unhealthy manners with others in the space. Especially in voluntary and relatively unmoderated spaces like museums, this raises a critical question of the balance between leaving space for flexible collaborations, supporting agentic experiences and encouraging participants to leave space for others (including unwarranted help, taking turns and letting others participate, and so on). Even in high modularity environments like App Inventor based programming, project work often took serialized structures, i.e., groups decided on ordered sets of steps to get to their final goal. In such plans, especially in computing environments, the development of driver/planner roles is frequent and is most commonly mitigated by scripted rotation of roles (Strijbos & Weinberger, 2010). Given this design framework, I expect the other designed affordances (awareness and intersections) to provide other inroads into supporting agency as well as mitigating the harm of solidifying such relative roles.

Related to the solidification of relative roles of participants, activities with low modularity sustain a limited set of goal orientation states. If there is a fixed order to do things, or a narrow set of overlapping tasks, learners very often tend to engage competitively. We repeatedly see this in museum exhibits (Griffin & Symington, 1997), and especially in the Rainbow Agents case with the five boys – without understanding anything about the system, they decided to start engaging competitively. This might be mediated through gendered forms of participation (Borun & Chambers, 1999), or through the perceived parity and intention of the two controllers (recognizable as pairs of controllers in arcades often oriented towards competitive play). But this tendency is also repeated in City Settlers, where in multiple playtests including the one highlighted in this work, their goals are initially defined as surpassing their peers' progress. This is likely a tendency learned from the motivational structures used in classrooms, the broad educational system, and also in many highly popular video games. Though both these instances showed learners' proclivities to assume competitive alignments, the systems' designs – in particular an intentionally designed high modularity – presented pathways into negotiations leading to changing roles and goal orientations which actually took place! It is evident that if there was indeed just one task to understand and do, the players would continue engaging competitively through their experience. This can be a productive motivational design for specific learning goals and designs, but does not seem appropriate for spaces where exploratory, expansive, and *collaborative* learning are key goals.

Table 7 presents a quick description of the main features across the studies in this thesis and how they exemplified/implemented task modularity.

Table 7. Studies' implementation of Task Modularity

Connected Spaces	**Rainbow Agents**	**City Settlers**
- Complex open-ended domain inherently (Programming & design around app development) - Modularity of projects and coding environment is critical in enabling borrowing, repeating, and remixing code. - Flexibility and control around design also enables them to rethink their goals as well as processes.	- To trigger thunderstorms which reward the whole garden, players need to manage a biodiversity that is hard to do completely by oneself. - Treasure boxes increase in complexity, increasing the challenge/need for collaborative activity by needing more alive plants in their vicinity.	- Blind auctions to acquire buildings creates the need to understand others' needs, negotiate deals to increase individually successful deals. - Different metrics for a city and different buildings with strengths as well as constraints present a complexity that involves choosing goals, strategies and evolving interactions.

5.2. PEER AWARENESS

Knowing about fellow learners is consistently recognized as a key component of (successful) collaborative learning and activity. In almost all definitions of collaborative learning, an awareness of what the collaborators know and are doing are considered integral in maintaining coordinated conceptions of the problem at hand, progress made and productive directions of problem solving.

Maximizing this peer awareness, in terms of knowledge and activity, is not optimal for open ended learning environments. Since we want to create environments that create space for learners to collaborate with agency and not be forced into working with constant coordination towards the exact same goals all the time, there is reason to look at the different ways peer awareness can be designed for and balanced.

There are two kinds of peer awareness that are often designed for and play evident roles in the design of our learning environments as well – knowledge awareness, and activity awareness.

As the name suggests, **knowledge awareness** refers to being aware of what others know. Lacking contextualized awareness of others' knowledge is a key hindrance in being able to seek help or coordinate on common goals in open ended spaces (Ogata & Yano, 2000). Connected Spaces was designed specifically to bridge this gap and is a clear example of what providing contextually relevant awareness can look like, and its strengths and drawbacks around fostering varieties of collaborations are discussed later in this subsection. In the lack of designed supports for knowledge awareness among peers, common social mechanisms reinforce many pre-existing dynamics and hierarchies of power. Help and knowledge continues to be exchanged among those who come with prior knowledge and their friends, and learners with sociocultural power – those who are able to see themselves as *belonging* to the space, community, or discipline, dominate help-seeking and collaborative exchanges. Marginalized and minoritized learners in such spaces, especially as newcomers, have fewer avenues to engage with prior expertise and engage with enculturation opportunities to move towards becoming central practitioners. While knowledge awareness tends to focus on domain and disciplinary knowledge, there is great potential in exploring the value of publicizing other social abilities of learners and practitioners as well. People might not identify as experts in a specific topic, but might have exceptional collaboration skills (as helpers, teachers, motivators, or others) which would be valuable to be able to share to different kinds of help-seekers. Relatedly, sharing awareness of and access to peers' social capital is also a design challenge that has potential to increase participation from newcomers and help peripheral participants become more connected and embedded across different networks.

Activity awareness refers to knowing what others are doing. In joint problem-solving tasks, activity awareness of peers is often considered a key factor in successful conceptual convergence and effective problem solving. These environments prescribe maximizing peer activity awareness through designed scaffolds and communication practices for learners engaging in such collaborative activity. As mentioned above and supported by our findings (elaborated later), high activity awareness often biases the way learners engage with each other in unproductive manners – with respect to diversity of collaborative forms, as well as the related conceptual engagements with the discipline at hand, especially in the context of open-ended learning environments. In particular, it often reduces the tendency of learners to choose different goals – following and repeating what others are doing becomes the de facto mode of engagement (which can emerge as parallel or competitive play). Thus, there is a need to understand how to balance activity awareness in ways that foster different kinds of collaborative interactions in ways that respond to the broader context of the designed learning environment.

As evident across my studies, peer awareness is not completely a designed factor, and heavily mediated with behaviors, preferences, and prior knowledge and relationships of the learners engaging at any point of time. Different forms of knowledge awareness exist between friends, classmates, acquaintances, and strangers, and the same designed affordances surface different dynamics across these different relationships.

There are many possible kinds of peer awareness beyond the scope of my current studies but worthy of attention in future work, for e.g., emotional awareness, and relational and cultural awareness. The latter two, similar to sharing information about people's social capital, is both critical to surface in learning environments in sensitive manners, but also a challenge fraught with tensions that need to be studied carefully.

Table 8. Impact of different levels of **Peer Awareness** on different features of collaborative interactions

Level of Peer Awareness	Goal Orientation	Social role taking	Negotiations (around goal and role coordination)
High	This feels unknown. High peer awareness seems to bolster prior goal orientations – increasing competitive or cooperative behavior. Sometimes, having access to extraneous information involved a change of goals (where modularity was an essential component too.	Knowing too much about others can make it harder to pick a partner or helper. More expertise is needed to work with others when overwhelmed with knowledge awareness. Seeing too much familiar or unfamiliar activity from others can bolster confidence or insecurity about relative expertise (I know all about what others are doing; I have no idea what's happening).	Interface replaces human interaction – knowing 'everything' needed leaves little reason to talk to each other in more open-ended ways. Rarely, seeing others engage in actions that are completely unfamiliar open up opportunities for conversation and negotiation.

Medium/ Balanced	Knowing what others are doing (activity awareness) is key to rich competition or coordination. This is a common pattern in game design, and a known requirement in collaborative problem solving. Knowledge awareness is key in knowing about potential goals to pursue, where current expertise lies, and so on.	(Balanced activity awareness/interference) creates prompts to collaborate. When people are doing their own work and see others' progress, or products acting on their space, there is a strong reason to understand phenomena together. (Balanced knowledge awareness) leaves space for learners/participants to understand each other in richer more subjective manners, and together establish their dynamic/role. Who is able to teach how much,	Balanced activity awareness is key in creating spaces for talking and negotiation. Awareness being "medium" or apt to foster negotiation is also strongly mediated by factors outside the designed tool – like the organization of the physical space (enabling or hindering activity awareness) and preexisting social networks (people working with friends).

	and to what capacity
Low	People don't know who to work with or don't know of their actions' impact on others or vice versa. Other factors need to play a role in making social interactions happen in such a scenario.

5.2.1. High Peer Awareness

As we experienced with **Connected Spaces**, having an excess of information can make it hard to figure out who to connect with – having 7-8 affinity icons in front of learners' names led to even us teachers not knowing how to parse what is known by a student from the interface. At the same time information that is not an appropriately detailed level also does not help understand the peer's context (an affinity for "debugging" having negligible use since everyone engages in different amounts of debugging, and it was not evident or in the classroom's shared understanding whether debugging was a unique skill or not). In programming environments, using a debugger can be a specific skill, but the lack of a shared vocabulary for different terms used on interfaces like the CxS skill lists creates a gap that needs to be bridged by other agents in the environment. In the context of the broader activity in the App Inventor program (i.e., independent small group projects), **knowledge awareness** set the stage for a specific interpersonal role – of **help seeker and helper** when interactions were initiated.

In City Settlers, we presented all cities' stats and resources on the central scoreboard display. This high peer awareness (in the form of activity awareness – where the progress and state of groups' cities is a marker of what they are doing), led to the interface **replacing many** possible occasions for **negotiation** and deals. Though missed interactions are often hard to observe, we saw multiple instances of players looking at the scoreboard and deciding who to talk to. Additionally, players also used the scoreboard mid-conversation to move to dealing with another team who had the resources they needed. The balance for this form of awareness, worked differently across different game mechanics. It hindered different forms of trade negotiations (earlier versions of the game where this information was hidden saw players engage in arbitrage by buying resources for cheap and selling them at a higher rate to another team), but also enabled more complex forms of bidding + trade negotiations. Future versions of City Settlers are being designed to reduce the level of detail around city state which might inform us more about what kinds of collaborative interactions are supported through a "medium" amount of peer activity awareness being provided (in contrast to "high" information in knowing all city stats, and "low" in knowing none of them). Since the activity displayed on the shared display was perceived as a kind of "goal" for most players (trying to maximize happiness, trying to accumulate different resources as much as possible), high peer **awareness in this form of final product** also led to an implicit **competitive** goal orientation. We have seen this in other work as well – shared markers of progress across participants are often read as competitive elements, even when unintended (Lyons, et al., 2015). This might not have occurred if the publicly presented information was around the inner functionings of the city, such as which buildings different cities are running, but would likely make it much harder for participants to choose specific goals. Though competitive activities in classrooms and learning environments are often seen as harmful and less productive than collaborative learning opportunities (Peppler, et al., 2013), complex activities like City Settlers still produced many negotiations and sub activities spanning different goal orientations despite a competitive orientation in participants' overall goal pursuits. Since participants were mostly competing, they treated strategies and underlying knowledge as valuable hidden information and rarely shared these across groups. This led to a lack of helper-helpee interactions across groups, but negotiations about actions across groups which in turn led to strategy negotiations within groups. Creating a player setup with these two different group relationalities was key in enabling different forms of interpersonal roles and negotiations happening around similar game events.

In Rainbow Agents, peer activity awareness was rather high, but took a variety of forms. "Final" decisions made by players, i.e., sending their agent onto the garden to conduct a sequence of tasks, was explicitly visible to the everyone around the exhibit (including non-players), and even interacted with the other players' work. In this case, what appears like high(/excessive) awareness helps create the concept of shared activity in a space (i.e., museums) where there are not pre-existing cues or reasons to engage with strangers. As discussed earlier, museums present a host of design constraints – from linguistic flexibility around audiences in Queens, New York, to designing for crowds that typically do not intend to stay at an exhibit for long. Socialization in museums as with many public spaces, is expected to stay within acquaintances, and work around social learning often examines just learning within friends and family. Though these existing acquaintances tend to be the stable groups and often determiners of one's learning experience at museums (McManus, 1987), using *high peer awareness* as a design heuristic, both for observing others' work as well as creating 'interference' with one's own work creates many more spaces for social work and learning even across people who do not know each other. As discussed in the Rainbow Agents chapter, a unique feature of interference through actions on the shared garden is the enabling of social interactions mediated through objects. New visitors are working with previous visitors through their actions on the garden, possibly working agents and state of the garden *a la* collaboration through the air (Halverson, Litts, & Gravel, 2018). This had a visible impact on the goals they chose – when players encountered dying plants from earlier gameplay, some players oriented their gameplay to save the plants rather than pursue treasure boxes. Additionally, the high peer awareness also allowed for onlookers to find entry ways into gameplay. Our SCAMP case highlighted the instance of young onlookers deeply engaging with the game before they got a chance to start playing.

5.2.2. Medium/Balanced Peer Awareness

Connected Spaces was cautiously designed to not overshare task information. Since it was designed to help connections among people working across disparate projects, informing other students about in-task progress felt like extraneous details. We expected knowledge about peers' expertise would provide adequate context to enable students to reach out to others. As mentioned in the last section, this focus on **knowledge awareness** (in addition to the context of a project-based classroom with students trying to complete their small group projects) set the stage for **helper-helpee relationships**. It is possible that providing more activity awareness could have created space for dialogue and negotiations around different integrations across projects, or other relationships and shared goals. These are productive lines of inquiry, rarely seen in face-to-face classroom scaffolding tools. Different games and online environments where people share works in progress have seen space for many more social configurations to develop (Steinkuehler, 2006), as well as more flexibly structured learning environments like makerspaces even without technological scaffolds (Halverson, Litts, & Gravel, 2018). Relatedly, the help seeking alerts were intended to be the only form of activity awareness reinforcing the helper-helpee role, but across groups which did not exist for the most part (i.e., students rarely worked or helped outside of their groups otherwise except through prior social friendships and connections).

Apart from the productive value of high peer awareness discussed in the last subsection, the limited but available access to other players' actions – enabled through visible but slightly distantly placed touchscreens which the players worked on – also had unique ability in rendering a variety of social configurations possible. As a result, onlookers not actively playing on the game often had greater visibility of players' active working, compared to the ability of players to see each other's work. This was intended to create space for needing to solicit joint action and discourage overreaching control over others' interfaces. We know from work on designing for interference in museums (Falcao & Price, 2009) that overlapping controls often lead to some visitors taking over aggressive control and not leaving space for others to act. As discussed earlier, this also reinforces the design imperative to foster turn taking behavior through interaction design in the museum experience. Through a variety of cases, we can see that soliciting joint attention and action allows for negotiations aimed at understanding and choosing certain goals (either in competition or coordination with each other), spanning different interpersonal roles (expert-novice, collaborator, "debater", or others). These conversations were about different in game goals like treasures, plant survival, or biodiversity, which in turn spanned a variety of underlying conceptual mechanics and learning goals, allowing for different entry points and learning journeys through visitors' experiences.

5.2.3. Low Peer Awareness

As expected, overall low awareness leads to a lack of novel social configurations from occurring. At the same time, partially removed peer awareness in the context of other intersecting goal and activity design, can spur learners to engage in a variety of ways. Most noticeably in City Settlers, we designed the bidding system to provide no information about other teams' bidding attempts and/or interests across the different kinds of buildings (in the marketplace). This led to the changing forms of negotiations across groups. Initially, players oriented themselves in parallel competition with respect to other teams – taking the form of trying to maximize resources – and their interactions were only negotiations around inquiring what other teams were bidding on. At most, players would ask others to bid for a different building, or a different version of the same building – not involving an actual negotiation over goals or roles, but simply coordinating actions to be in complement (and occasionally covert competition when players used others' bidding information to outbid them). Eventually, when players recognized the interconnectedness of their actions (through interfering pollution, attempting to balance happiness and population as byproducts of their chosen buildings), their inquiries about bidding actions began including conversations about strategies and more deeply interconnected ways to balance each other's goals. Productive co-operations took place when players were able to balance trading resources with different decisions about buildings to bid on, and in the process also nudge each other's strategies in different directions.

5.3. INDIVIDUALIZATION

A key design feature in supporting flexible and evolving social configurations tends to be space to do individual work. For our desired goals of collaborative interactions – the occurrence of negotiation around goals, and interpersonal relationships – having space to learn by oneself, and do disjoint activity for some periods of time, enables critical 'individual' growth which learners can then use with and against each in diverse ways.

In the context of museums, where user control is often elicited and supported through tangible interactions described as multiple access points by Fan, et al. (2014) building on Hornecker's (2005) description of the design concept. Multiple access points consider the value of providing controls that allow for learners/participants to engage with autonomy, but also be able to engage in shared attention and joint action. Too many access points, even in a shared space, leads to parallel play (Inkpen et al., 1999) and too few access points (either as actual separate interfaces or devices, or in the separation of influence from different controllers) leads to domination effects where a few players take control for a majority of the time (Marshall, et al., 2009). This prior work clearly resonates with the implication of access points – a form of individualization of interfaces and control – on goal orientation in social/collaborative play. Fan, et al. (2014)'s usage of intersecting access points in collaborative play to initiate deeper conceptual conversation (i.e., emergent dialogue) is also discussed in the City Settlers chapter. This is indicative of how individualization impacts the social roles and negotiation component of collaborative interactions in such environments.

As discussed further in the subsection on low individualization, a lack of individual feedback often leads to solidification of roles (within and across groups) that only seldom evolve. Work on emergent roles often finds the need for partial scripts to resolve this tendency and create mechanisms to rotate roles across learners to afford equitable learning opportunities. This is frequently hard to exercise in informal learning environments, and even when implemented, often reduces learner investment in some of the roles. This scripted rotation of roles is particularly poorly suited to richly foster learner agency and personally authentic experiences.

Table 8. Impact of different levels of **Individualization** on different features of collaborative interactions

Individualization	**Goal Orientation**	**Social role taking**	**Negotiations (around goal and role coordination)**

Level			
High	People start doing their own thing and just stick with it.		
Medium	People able to work by themselves frequently. This creates more middle grounds for revising goal orientation. When participants learn new things, or revise their personal goals, there are spaces for competition to become coordination and vice versa.	People generate separate understandings they are able to teach others about, or even argue about.	There is more reason to work within groups than in spaces where the work pieces could be entirely divided up. Particularly valuable in creating space for diverse groups so players can delve into distinct interests, generate specific understandings, and interact with each other in unique ways (within group or across group; competing or coordinating).
Low	People are not able to pursue things specific to their interest.	Dominant players start assuming expert roles fixing	Dominant players/drivers take control, often leaving others out of participation

	Dominant players' participatory preference to compete or coordinate take precedence, not allowing for different kinds of participation from individual group members.	(correcting or directing) others' actions and imposing a "subordinate" role.

5.3.1. High Individualization

A primary outcome of high individualization is when players start spending most of the time **just working individually**. This is not necessarily a drawback – interacting socially, especially in open ended learning environments should be agentic and not forced in the design as much as possible. For instance, much work in classrooms tends to lean towards being highly individualized or social in highly regulated manners. Notably in the App Inventor classroom – the need for assess-able project work from groups sets the stage for students to prioritize their small group work, and not use much of their time and capacity in engaging socially (in the context of programming work) outside of their small groups. This is to say there are contextual uses for providing space for individualized work which hamper (or don't force) social connection – and that other design affordances can still be used to create space for potentially productive social interactions. Also, there is an underexplored design space in how to create space for evolving social relationships within tightly coordinated small groups. This is discussed further in the low individualization subsection.

In Rainbow Agents as well, the individual controllers often leave space for individuals to work independently and just by themselves. We have seen this in prior museum design and is a known design pattern – providing controls for multiple participants to play leads to parallel play more than collaborative play. There is a tension between the independence of player controls and the social connection visitors are able and willing to bridge among each other. Visitors who already know each other, or are willing to socially engage with each other, often overcome individualized design patterns by talking with other visitors taking up a variety of roles – instructors, drivers, helpers, friends, askers and help-seekers. Visitors who prefer working alone are able to work by themselves, until there are other designed reasons to engage with others.

5.3.2. Medium Individualization

The goal of individualization is to create opportunities for developing understandings which can contribute to richer social interactions – exploring the possibilities of different goal orientations as well as the social role relative to other learners. In the App Inventor environment – similar to other flexible maker environments – having a personal toolkit, i.e., computer and testing device for each student was critical in letting and helping them learn how to solve their specific subtasks autonomously. Herein I refer to a conception of autonomy comprising epistemic maker and computing skills (Regella, 2016) which includes learning how to look for resources, ask for help, and redesign their project in response to technical and social constraints (limitations of the tools at hand as well as ability to solve problems in the available time to present a prototype). This individualization worked most richly when exchanges of help turned out to be beneficial. Our CORDTRA analysis depicted how the ability/knowledge to use different modules moved across the classroom (Tissenbaum & Kumar, 2019). Many of these were either learned from non-peer sources like previous examples, the internet, and asking the teachers, but it was also propelled by peer helping and teaching. This as well as cases from prior pilots and other environments show how helper-helpee interactions, can look unilateral (in terms of "benefit" or knowledge transfer) but often also help improve the helper's understanding and usage of the same skill, as well as benefits them with mentorship opportunities in terms of identity development (Hilsdon, 2014). Access to such mentorship opportunities need to be designed for and specifically provided to learners who don't often get a chance to see themselves as experts in the domain, and having the ability to mentor others (for instance, heavily minoritized learners in computing in the United States include women and Black, Native American, and Latinx learners, who need and deserve mentorship and mentoring opportunities in ways that support them and also inform what is recognized as productive mentoring styles in the broader computing practices).

In Rainbow Agents, similar to the discussion around *medium peer awareness*, the approachable distance between the two individual controllers was key in players being able to change their goals through individual play, and also develop different understandings about the game's mechanics. Being able to see others' progress, on the central garden display as a peripheral viewer, or look at others' individual controller actions over their shoulders, were also ways of being peripheral participants and having individual learning opportunities. This was most exemplified in case 1 where the younger newcomers started their gameplay with already formulated understandings and goals and were able to debuff instructional moves from the older player to prioritize their own interests. They had acquired these goals while being peripheral viewers before they got a chance to start playing. At the same time, they did engage with the longer duration player and used his advice to guide some of their actions. Additionally, in case 2, the group of 5 boys changing their goal orientation from competing with each other to a cooperative learning exchange was heavily supported by the players' ability to play separately, try out different things and share their ideas with each other when they saw opportunities to guide each other.

In City Settlers, the individual trade interface was expected to be the avenue for individualized action – a space for players to make decisions that affected their whole group, but also gave them opportunities to engage with members of other teams. In our playtests, trading as a mechanic was too tightly intertwined with the information available only at the base tablet, and left too little space for individual action, more concretely discussed in the next *low individualization* section.

5.3.3. Low Individualization

As referenced earlier, **small group coordinated work** often leaves limited space for individualized work, leading to a **common pattern of driver-passenger** roles emerging (Strijbos & Weinberger, 2010). Similar to how low modularity works, environments with limited individualized control-feedback often paves the way for dominant players taking control and directing others' actions. In the App Inventor activity, small group work took place with a fixed goal orientation by design (all team members *have* to coordinate towards a completion of the same project) – leading to groups with different interpersonal relationships ending up with potentially unhealthy dynamics. While we did not find an explicit case for this in the App Inventor activity (though as mentioned earlier, this is a common occurrence in many maker activities, project-based classrooms and computing activities), our case from City Settlers found multiple overt instances of this.

In our City Settlers playtest, some students were able to understand many of the game mechanics quicker than their teammates. This created a situation similar to how low modularity works – some of the group members were able to make all the decisions and conduct tasks which they found important, not leaving much space for other team members to do much. This was mediated through the social positioning of the members relative to each other and the activity as well – our case points to how a team of 2 (Asian) boys and 1 (White) girl happened to leave the girl sitting alone at the table for the most part with many attempts at participation left largely unheeded. Similarly, another team of 2 girls saw the 1 White girl conduct most of the actions, and only rarely see instances of her teammate (a Black girl) being able to participate. Those events were also often through prompts and support from the more active girl. We don't have enough data to say much about how race and gender affected how the participants saw their teammates and felt engaged or not in the activity at hand – but innumerable studies around gender and race in classrooms hints at their likely effects on this environment. At the same time, we know that unlike a low modularity situation – the *drivers* did not actually know everything from the start. There were evident moments of understanding new concepts as the game progressed. A key design shortcoming here was that the "left behind"/marginalized players who missed out on (aspects of) a meaningful gameplay experience, were not able to do anything by themselves when other teammates made decisions about city management (in particular the bidding and trading mechanic). Though we had expected the individualized trading mechanic to be the space for players to exercise their agency and learn new things by working and talking with other teams, this relied on having shared access to the city's base tablet. Using tablets for the base view worked poorly when some team members started carrying the base tablet around during all their actions, leaving minimal information for other teammates to work with. This experience could have been ameliorated with more information or exploratory tools on the individual interfaces for learners to decipher the complex systems in action by themselves, when not engaging in dialogue and collective action. It is critical to understand how more or less individualized interfaces succeed in richly engaging a plurality of learners, participatory styles, and learning goals.

This slice of looking at collaborative interactions (Goal Orientation, Role Taking, and Negotiation), is most unique in the expanded considerations afforded through the spectrum of different goal orientations in a given environment. Other (research and design) lenses on open-ended learning environments, including those on emergent roles, often implicitly assume working on a shared or prescribed goal as an implicit premise of learning situations. Recognizing the multiplicity of participant goals that can exist in a learning environment and how they are exhibited in relation to each other, is a key underexplored topic in the design and research of social/collaborative learning environments.

It is critical to remember that rich complex experiences are created at the intersection of learners and the environments they are in and analyzing these experiences at different levels affords richer understandings of what benefits learners and how. The analyses in this dissertation focuses on learning environments as collaborative, which host episodes as collaborative experiences, which in turn are made up of interactions with different kinds of collaborations. Specifically, I want to highlight how the focus on the diversity of collaborations in this work needs to be accompanied with future work focusing on collaboration as a process of evolving relationships, and not just discrete states inherent to the design or to the learners. Relatedly, the vocabulary set up in this section (in particular Task Modularity, Peer Awareness, and Individualization) presents an initial attempt at thinking about the design features that can better foster such rich experiences and can also be parameters for research and iteration for different learning goals.

Chapter 6: Conclusions

This dissertation began with discussing the different ways collaboration and collaborative learning have been studied in educational research, largely in the learning sciences. Existing work and conceptions helped provide the three broad components of collaborative interactions I focused on – goal orientation, social roles, and negotiations. These categories mapped to how learners' actions relate to each other, how they relate to each other as people in the space, and how these relationships change over time. This conception implicitly considers collaborative episodes/experiences to be made of multiple interactions which can change (according to the aforementioned features). This unit of analysis was used across the presented studies – where the environment is considered a collaborative learning environment, and the ways that learners can, and choose to collaborate with each other, changes over time as they interact with different affordances of the environment.

I began with describing the work around Connected Spaces – an ambient help-seeking interface, situated in a computing project-based classroom. The classroom environment presented particular constraints in terms of how students knew each other, and how the constraints of a class pushed them to manage completed projects by an end time. As a result, we saw how the design of Connected Spaces initially fell short in facilitating organic peer-to-peer mentoring opportunities. Instead, we saw the tool as useful for teachers to become more competent brokers and facilitators of inter-group peer learning events. This study shed light on how classroom cultures often impose constraints on the potential of a design (and student behavior itself), especially with respect to emergent collaborative behaviors, and how teachers will often need to be key mediators of changing these cultures. Other features about the design of Connected Spaces which we revised informed our broader summary of how balancing task modularity and peer awareness presents unique informational design challenges that continue to be ongoing projects.

This was followed by the analyses from Rainbow Agents, an interactive social museum game around computing concepts. Here we again observed how the context of the learning environment, and people's prior proclivities can lead to the fostering of unexpected kinds of social interactions.

The development of SCAMP, the analytical framework for describing and understanding the relationship between exhibit design features and the kinds of collaborations supported in this space, heavily informed the broader framework described discussed in the last section. Similar to Connected Spaces, we observe learners' transition through and access different forms of collaboration. In contrast, the designed features of the game themselves were able to support this transition of collaborative interactions and did not rely on "external" forces (like prompts from others). As discussed in the value of context, this was potentially afforded by the ways game-based learning is able to guide and channel learner interactions more than open-ended project-based learning activities and open up different interactions and goals for learners as their understanding evolved through their gameplay (for instance, engaging with shared rainbow plants after successfully opening a few treasure boxes individually or collaboratively).

Lastly, we presented the analysis of different kinds of collaborations reflecting enactments of (understanding) different systemic phenomena around City Settlers – a mixed reality city planning simulation played by small groups of learners managing independent but interconnected (virtual) cities. Here the in-game mechanics coupled with the affordances of the design of the tools and artifacts in the environment, led the players to pursue similar city development goals. As they engaged in this pursuit, they uncovered the consequences of competing, and eventually engaged with the need to negotiate and create interdependent alliances for more sustainable growth. This was a uniquely enacted understanding of real-world phenomena through different collaborations – where the relationships between intersecting systems (like different cities, states, nations) are actually maintained through different needs, resources, and interpersonal negotiations. This provides us with an example of designed constraints which lead learners through different collaborations creating a community of learners and developing shared (and divergent) complex systems understandings at the same time.

Here, we have discussed a particular summarization of the design patterns across my studies that played overt roles in affecting the nature of collaborative interactions across – task modularity, peer awareness, and individualization. While there is a motivated analytical structure (specifically the components of design embodiment from Sandoval's Conjecture Mapping) that justifies this choice, there are a host of other frameworks (Latour's Actor Network Theory (Latour, 2005), and Engeström's Activity Theory (Engeström, 1999) to name a few) that would afford complementary lenses into the different phenomena and design-effect relationships that are surfaced from these studies.

Some of these design patterns are more in control of designers than others, but as with all design, the extent to which a design pattern acts on the scale of high to low, is a result of the interplay between the environment design and the learners. This makes it hard to identify in advance whether a certain design of task modularity is appropriately "balanced" when in action, especially across different kinds of learners. But I hope this model, and further work that builds on it, is able to provide some guidelines that inform design iterations when emergent social interactions lean towards an undesirable end of a particular feature.

These balancing recommendations have been occasionally mentioned through the sections. A common challenge that occurs in collaborative learning environments is high amounts of parallel play – where learners don't engage with each other in tasks and keep acting in disjoint manners. This can become both competitive when learners choose to repeat the same task or be disconnected if they engage in different tasks and do not see any connection between each other's work. The former can possibly be balanced by increasing awareness in contextually relevant manners, and the latter can be balanced by reducing task modularity in ways that make similarities and intersections between different tasks more visible.

The inverse is also a common challenge – where groups of learners see inequitable participation as some learners take up self-appointed leadership roles and take unsolicited control over others' actions. This is a common problem that is often combated in a variety of ways. From our design patterns, increasing task modularity and creating more individualized workspaces are potential avenues to support group members in engaging in different tasks while also gaining competence in a way that helps them be a valued member of the group.

The broad categories used to look at collaborative interactions also provide a valuable lens to look at how learners are interacting and relating with each other in a space. Thinking about the different goal orientations one's design supports, and which ones learners choose to engage with, can inform how to revise one's design. While coordinated action is often seen as the gold standard of collaboration, we have seen examples of the value found in allowing for healthy amounts of competition and even parallel play. Almost all coordinated work projects (/joint problem-solving tasks) see instances of parallel work. Identifying these as opportunities for conscious design to support productive learner growth has great potential in improving learner experience and understanding a fuller plurality of useful participatory ways of learning. Most critically, supporting a fuller variety of (social) learner participation is key in creating more equitable learning environments. There is an increasing drive to recognize different learners' participatory forms as needing recognition as valid and valuable ways of knowing, talking and being learners and practitioners (Mejía-Arauz, et al., 2018; Espinoza & Vossoughi, 2014; Uttamchandani, 2019; Agarwal & Sengupta-Irving, 2019). In this spirit, I hope this work helps expand what is considered productive collaboration, and also guides and pushes learning environment design to consciously design for and support broader categories of (social) behaviors.

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