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Design for Learning Through a Complexity Perspective: A Board Game Redesign Approach to Enabling Learning Possibilities

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Design for Learning Through a Complexity Perspective:
A Board Game Redesign Approach to Enabling Learning Possibilities

by

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A THESIS
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Abstract

This doctoral study followed a conception of learning as a complex phenomenon and aimed to examine the possible ways of supporting it. Drawing on insights from complexity research, particularly the notion of enabling constraints (Davis & Simmt, 2003), my research explored the settings for supporting learners’ agency in pursuing their ideas and interests, while stimulating new possibilities of collective understanding and action. These goals were pursued through a design-based research on the potential of a board game redesign approach in providing the settings for complexity-informed design conditions. The following questions guided this research: How would a board game redesign approach provide the settings for enabling constraints? How would learners’ co-design practices evolve through the game redesign process? and How would learners’ decisions, ideas and interests frame their designs and open the space for using math and science in creating game systems?

The synthesis of the literature on complexity views in the learning sciences addressed how these perspectives could conceptually frame learning designs. In addition, this review highlighted the lack of design studies examining the proposed design conditions. Through two phases of design-based research, my dissertation explored ways to incorporate complexity-informed conditions in practice and to enrich the understanding of learning processes and investigated what supporting learning as an emergent phenomenon entails.

Using the framework of enabling constraints, the first phase analyzed the commonalities and variations in students’ collaborative practices in redesigning the board game Inversé for mathematics learning, in an elementary classroom. This analysis highlighted the importance of structured constraints at the starting point, which included students’ playing the same game and aiming to redesign it, in supporting a common language. At the same time, it indicated the interconnection of the constraining and enabling aspects of the developed commonalities throughout the process. Learners’ emerging idea exchanges at the class and group levels and reaching higher conceptual possibilities were enabled as they developed shared goals and understandings through the project structure and cycles of unfolding co-design.
The study conducted in the second phase was a design iteration of the learning design examined during the first phase with more explicit use of complexity-informed conditions. The design in the second phase focused on engaging middle school students with math and science topics through a board game redesign approach where students redesigned the cooperative board game *Pandemic*. A modified analytic frame was used in the second phase, using the notions of divergence and convergence of ideas and self-imposed constraints from design and creativity research (Biskjaer & Halskov, 2014; Stokes, 2009) to focus more on the processes of the evolution of learners’ practices and understanding. The findings elaborated on how the board game redesign approach, and the materials and activities involved, not only set some structures but also enabled students to negotiate their interests and choices and collectively make decisions. Learners’ interests and decisions acted as self-imposed constraints that framed their work and, at the same time, could expand their design space and engagement with math and science topics.
Preface

This thesis is original, unpublished, independent work by the author, Reyhaneh Bastani. The studies reported in Chapters 4 and 5 were covered respectively by Ethics Certificate Numbers REB15-2503 and REB18-0001, issued by the University of Calgary Conjoint Faculties Research Ethics Board for the projects “Students as Game Designers” on October 29, 2015, and “Design for Learning Through a Complexity Perspective” on August 12, 2018.
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Chapter 1: Introduction

When knowledge is conceptualized as distributed and dynamic, learning can be seen as a matter of expanding capacities to adapt to novel circumstances. The shift in the view of knowledge and learning can open new perspectives toward designing learning environments. These perspectives specifically challenge the approach of structuring learning environments to achieve pre-specified goals for all learners. They promote understanding learning not as linear and controllable, but as emerging through expression and interaction of alternative interpretations and diverse interests (Davis et al., 2015; Doll, 1986; Mason, 2008).

Complexity perspectives in education have attended to studies of learning as a phenomenon emergent at different levels, i.e., individual and collective. In organizing learning environments, they advocate design for learning with interactive, divergent and dynamic approaches, veering from linear and sequential views (Davis & Sumara, 2006; Doll, 2015; Osberg & Biesta, 2007). Scholarly work in this area has been informed by complexity research developed across different areas of knowledge, such as mathematics, life sciences, and social sciences (e.g., Holing, 2001; Kauffman, 1996). Studies on complexity probe how diverse rule-following entities interact and shape a collective whole that shows emergent behaviour, as they learn, adapt, and evolve. Complexity perspectives in education have attended to the interconnections among phenomena of interest in education, such as knowledge systems that include individual understanding and collective knowledge and matters of concern ranging from biological to ecosystemic wellbeing. They evaluate individual sense-making and collective understanding as emergent and interdependent and argue for learning designs that consider agency, creativity and diversity at the individual as well as collective interaction levels (Davis et al., 2015).

With the explicit use of insights from complexity research, this research intended to explore the conception of ‘learning’ as a complex phenomenon, and to examine the possible ways of supporting it. This included exploring the settings for supporting learners’ agency in pursuing their ideas and interests, while stimulating new possibilities of understanding and action for the collective. These goals were pursued through a design-based research on the potentials of board game redesign in providing the settings for complexity-informed design conditions.
This dissertation is structured as follows. The first chapter explains the research rationale, the research questions, and the methodological approach of this research. In the second chapter, I provide a review of the literature. This review addresses the notion of complexity and the development of complexity research in different areas of knowledge, and how this body of research has contributed to the field of learning sciences. Through the review of literature, I position this dissertation’s focus, considering the existing and ongoing complexity-informed research in the learning sciences, and discuss the conceptual framework that informed the study. The third chapter describes my research design, starting from a brief description of design-based research and the alignment of this approach with my doctoral research’s conceptual bases. It also includes the descriptions of the study context and methods of collecting and analyzing data, and the ethical considerations in the implementation of my research. The fourth chapter addresses a complexity-informed analysis of an implemented project on student mathematics learning (first phase of the study) through board-game redesign, i.e., analyzing an already implemented learning design based on the notion of enabling constraints elaborated by complexity perspectives. The fifth chapter describes a math and science learning project through a board game redesign approach. This project is designed and analyzed explicitly using complexity-informed conditions (second phase of the study). Chapter six includes a discussion on the findings emerged across the phases of this study. Finally, the conclusion provides a summary of this doctoral research process and addresses its limitations and delimitations and future research directions that could stem from this work.

**Purpose and Research questions**

Traditional views of managing classrooms with the aim of pursuing preset outcomes have been growingly challenged (Bereiter & Scardamalia, 2003; Ke, 2014; McGregor, 2004). Deterministic approaches to learning not only set the same learning objectives for all, they could also channel a varied range of interests, needs and ideas into a specified direction, i.e., limiting or controlling the diversity existing in the classroom.

Questioning such intentions, contemporary views of learning argue for creating educational experiences building on the existing diversity in classrooms as a critical source of learning (Davis et al., 2015; Doll, 2015; Rosebery et al., 2010). These perspectives promote a conception of knowledge as distributed and evolving. Learning is viewed as emergent and a
matter of individuals and collectives expanding their scope of interpreting phenomena and possibilities of understanding and action. It involves multiple elements, such as learners’ diverse experiences and the interaction of heterogenous points of view within their social and material environment (Mason, 2008; Sengupta et al., 2021; Wertsch, 1998).

Importantly, such discourse on learning speaks to the requirements of our constantly changing world: individuals should not only specialize but also have the flexibility and adaptability to deal with complex and uncertain situations. Such adaptability entails interpreting from various perspectives, i.e., imagining and participating in possible scenarios and situations to make an impact.

For educational researchers, any description of knowledge and learning should attend to what is advisable for creating knowledge and supporting learning. The field of learning sciences is specifically concerned with studying the processes of learning and the possible structures that could support learning. This dissertation attends to how we could design for learning experiences that leverage the existing diversity of ideas, interests and intentions, which potentially trigger different levels of complexity in classrooms. Some researchers have explicitly used complexity research to address learning, specifically the design conditions to support learning that appreciate and build on the multiplicity of learners’ ideas. Designing learning environments based on complexity perspectives requires educators to recognize that understanding is not instantaneous and linear but happens cumulatively through the consideration of multiple arguments and reflections (Doll, 2015). These views particularly describe individual sense-making and collective understanding as emergent and intertwined (Davis & Simmt, 2003).

Complexity perspectives of design, therefore, assert simultaneously considering the individual learners’ agency, creativity, and interest and the collective learning systems in supporting disciplinary and interdisciplinary learning. They specifically use the notion of enabling constraints (Davis & Simmt, 2003). This notion points to creating the settings for learners to engage in common experiences, such as shared projects and tools to support their interaction and communication and, at the same time, enable different ways of contribution and diverse responses.

This dissertation addresses what complexity perspectives offer for analyzing and designing learning environments. It specifically focuses on the following overarching question:
How would a learning design based on the notion of enabling constraints help learners bring their interests and unique ideas into personally meaningful and productive disciplinary learning?

Studies on design-based learning show how design practices could provide the space for learners to collaborate and develop shared goals while pursuing their interests and ideas (Kim et al., 2015). This speaks to the potential of design practices in providing the settings for enabling constraints. Learning sciences scholars have studied games as models of systems for their potential to embody disciplinary and interdisciplinary knowledge (e.g., Ke, 2014). The recursive and open-ended task of co-designing games on curricular topics could open the space for students’ imagining possibilities of using learning topics and constructing new relationships with knowledge systems drawing on their interest (Kim & Bastani, 2017; Li, 2010).

In the study conducted as part of this dissertation, a board game redesign approach was used considering its potentials in implementing the complexity-informed design conditions (i.e., enabling constraints). Re-designing board games, in which learners play a common board game and change its elements to create their own games, provides the settings for a common starting point. The physical materials (e.g., the components from the board game to be redesigned) also help learners develop shared communication channels and collective goals. In the iterative process of design and getting feedback, learners would revisit their assumptions and understanding of problems and explore new ways of using learning topics. Through the study conducted based on this game redesign approach, this dissertation explores the following questions:

1. How would a board game redesign approach provide the settings for enabling constraints?
2. How would learners’ co-design practices evolve through the redesign process?
3. How would learners’ decisions, ideas and interests frame their designs and open the space for using math and science in creating game systems?

This design-based research aims to contribute to the theoretical and practical understanding of classroom communities as emergent learning systems. From a theoretical perspective, this could expand the understanding of the complexity of educational settings that
has been reflected through different descriptive frameworks, such as those focused on the situativity of knowing and learning (e.g., Greeno, 1998). Through the study based on a board-game redesign approach, this dissertation aims to specifically expand on the notion of enabling constraints discussed by complexity perspectives. To this aim, it explores the interim processes that support learners to bring their ideas and interests into negotiation in their collective practices and develop their unique paths of engaging with learning topics while pursuing their collective purposes.

Methodological approach

This study’s approach takes root in the assumption that “reality is holistic, multidimensional, and ever-changing; it is not a single, fixed, objective phenomenon waiting to be discovered, observed, and measured” (Merriam, 2009, p. 214). This view undermines evaluating the data collected based on its representativeness of the truth, as traditionally reflected in measures of validity. What makes this type of research trustworthy is the researchers’ “critical presence in the context of occurrence of phenomena” (Kemmis, 1983, p. 103), observation, and triangulation of participants’ perspectives and interpretations “to uncover the complexity of human behavior in a contextual framework” (Merriam, 2009, p.215). This dissertation tries to pursue this in the procedures of data collection and analysis as well as how they are communicated to the reader: “the qualitative research provides the reader with a depiction in enough detail to show that the author’s conclusion ‘make sense’.” The world they portray is not one of variables and static states, “by contrast, the qualitative study describes people acting in events” (Firestone, 1987, p. 19). Specifically, collecting data for long periods in different iterations, which allows for continual analysis as well, and using multiple sources of data was used as strategies for increasing the credibility and trustworthiness of research. Importantly, reflexivity in the process of analysis and communicating findings could contribute to clarifying the researcher’s and other participants’ (mainly teachers) past experiences, values, interests, intentions, and theoretical approaches in relation to the study (Merriam, 2009; Simons, 2009). This helps the reader make a better sense of how the researcher “might have arrived at the particular interpretation of the data” (Merriam, 2009, p. 214).

This is also connected to the matter of the research being of value for other researchers and practitioners in other situations. Addressing this matter is not about whether findings will be
found again, or the processes being replicable, as assumed in the accounts of reliability. Rather, it is about the consistency of the process, the data collected, and the results of the research. To this end, this dissertation attends to providing a detailed description of the assumptions, the settings and participants, how data were collected, and how decisions were made when facing emergent issues and ideas throughout the study. This approach could help others better evaluate the relations and similarities between their contexts and this study’s. It, therefore, could contribute to new understandings of the phenomenon of interest in other contexts, and trigger new practices. Besides the discussed strategies, providing the project history “in the form of a diary or log of processes” (Richards, 2005, p. 163) was used in this regard (Merriam, 2009).

Complexity perspectives, which conceptually frame this doctoral study, describe the issue of evaluating the research findings and claims in terms of how they contribute to “model-ability” and adaptability of the system under study. The issue would then be whether the phenomenon could be modeled, and “similar systems [could] be triggered into being,” and whether the understanding of the system could contribute to its viability and fitness to its environment (Davis, 2018, p.14). Design-based research, an approach rooted in complexity views, could specifically focus on these matters, being defined based on studying social systems in multiple contexts, and attending to both exploration and transformation of those systems.
References


Chapter 2: Conceptual framework and Literature

The present literature review addresses the notion of complexity and the development of complexity research and explores the contributions of complexity research in the field of learning sciences. Specifically, I focus upon two strands that I have identified in the literature. First, I examine how scholars have used complexity as a frame to study knowledge and learning, conceptualized as emergent phenomena, and to create the settings for individual and collective understanding. Second, I investigate the research supporting students’ understanding of complex phenomena that contributes to their disciplinary and cross-disciplinary learning, using different tools and environments.

This review is outlined in four sections. The first section reviews the descriptions of complexity and the qualities of systems that are characterized as complex. In the second section, I provide an overview of the main trends in the development of complexity research. The third and fourth sections explore the contributions of complexity research to the field of learning sciences in two different ways, as mentioned above: (1) the studies using the complexity framework to understand and structure learning systems. This part includes a discussion of complexity in relation to the theories concerned with the emergence of learning at individual and collective levels (i.e., constructivist/cognitive and sociocultural approaches), and the pragmatic views that incorporate complexity to provide frames to structure learning systems; (2) the design studies attempting to help students develop a complexity perspective of the real world. I conclude by suggesting the possibilities of using the two strands of research for learning scientists, considering their theoretical and practical implications in designing learning systems. I also position this dissertation within this literature discussing learning design considerations informed by this review of the literature, and potential contributions and implications.

The historical map (Figure 1, also accessible at https://bit.ly/3fYWrI0, Bastani & Kim, 2021) that follows the first section, is created as part of this literature review to develop a historical understanding of the major trends in complexity research and complexity views in education. The circular and oval shapes in this map represent seminal ideas, conceptual frames and practices that initiated or contributed to these identified trends. The first row of this map provides a historical view of the leading work that has informed the development of complexity
research in mathematical and physical sciences, life sciences, and social sciences, addressed in
section two. The other three rows illustrate an overview of complexity perspectives in education.
These include theories of knowledge and learning that are compatible with complexity views
(second row), as well as the explicit contributions of complexity discussions to education (third
and fourth row) which I elaborate on in sections three and four.

**Complexity research and complex systems**

Complexity research has been developed to describe a diverse range of complex natural
and artificial systems across different fields from computer science and electrical engineering to
biology and sociology. This makes offering a unified and precise description of complex systems
very challenging (Walby, 2007). In a general sense, complexity research aims to explore how
diverse rule-following entities interact and shape a collective whole (i.e., a complex system).
These entities, or *agents*, learn, adapt, evolve and form a system, which shows emergent
behaviours and collective patterns without benefiting from a central controller (Mitchell, 2009;
Page, 2010). Investigations on complex systems, attribute a number of key qualities to these
systems, such as multiple elements (agents), self-organization, and emergent and adaptive
behaviours. Holland (2014) distinguished complex adaptive systems (i.e., social and biological
systems; CASs) from complex physical systems (e.g., star clusters and their formation), and
explained that in CASs agents are not fixed. Considering our interest in human learning systems,
I briefly discuss some of the key qualities of *complex adaptive systems (CAS)* that specifically
comprise biological and social systems.

**Qualities of complex adaptive systems**

*Multiple elements* in complex systems are irreducibly intertwined. They exchange
information dynamically on a network or contact structure (e.g., in a nervous system, an
ecosystem, or a market). The elements or *agents*, which themselves could be considered as
subsystems with interacting components (e.g., a nervous system as a subsystem of a human body
system), are not fixed but *adapt* or *learn* as they gain experience in constant communication with
other agents. This adaptation involves the modification of agents’ strategies in new
circumstances, resulting in the co-evolution of agents (e.g., co-evolution of traits between
different species) and the collective behaviour of the system (e.g., generation of new species and
changes in biodiversity in an ecosystem through time) (Cilliers & Spurrett, 1999; Holland, 2014).
Prigogine and Stengers (1984) associated this constant change in internal structures (i.e., agents’ behaviours and their interactions with other agents, various agents’ mutual dependencies, and the system's overall behaviour change) to non-equilibrium processes and the resulting self-organization in complex systems. Holland (2014) discussed that “it is unusual for CAS agents to converge, even momentarily, to a single optimal strategy, or to an equilibrium” (p. 8). As the agents adapt to each other, new structures with new strategies arise, offering new possibilities for agents’ interactions and evolution. Such feedback loops form new specialized agents and increase the diversity in the system and, consequently, its global complexity.

Holland (2014) asserts that understanding the interactions of adaptive agents in complex systems can help in providing solutions for today’s significant issues, such as improving the immune system, making ecosystems sustainable, and prompting innovation. This description is also linked to emergence, another major concept in CAS. Emergence is described as the macroscopic behaviour of systems that arise from the micro-level actions and interaction of elements over time (Kwapień & Drożdż, 2012). This notion is tied to the concept of levels in complexity research (Simon, 1977). Emergence addresses the relationship between levels and how higher levels arise from interactions at lower levels. It specifically rejects reducing the scale and quality of collective behaviour of systems merely to the sum of individual elements, whether individual agents in a society or atoms in a chemical compound, or to a “leader” agent with centralized control (Holland, 1995; Walby, 2007).

Scholarly work has used these attributes to evaluate a broad range of complex systems, from physical and biological to social systems. There are, however, discussions on the proper approach to attributing the discussed qualities to systems of various kinds. Some have challenged the objective approaches to understanding complex systems. Mesjasz (2010) specifically distinguished social systems as observant-dependent systems. He asserted that “in all discussions on complexity of social systems composed of conscious elements, the role of observer/participant must be always taken into account, even when studies concern objectively defined complexity” (p. 709). Tsoukas and Hatch (2001) also addressed an interpretive view of complexity, arguing for the active role of the observer in a social system in making sense of interconnections in context and their evolution over time.
Providing an overview of the development of complexity perspectives, the following section includes more elaboration on the different approaches to understanding complexity.

**Figure 1**

*A historical overview of the seminal work in complexity*
A historical overview of complexity research

In this section, I provide a historical review of the significant trends in the development of complexity perspectives across the different domains of mathematics, physical sciences and engineering, life sciences, and social sciences. This review aims to cast light on the ways that the leading scholarly works have chosen to explore various complex systems. Importantly, it intends to explore the roots of complexity discourses that have offered novel tools for addressing the learning content of educational projects, and at a different level, new epistemological considerations to educational researchers for understanding and design of learning systems. The first row of the map in Figure 1 visualizes the “Leading/Informing views”, exploring the historical trends in complexity research which are further discussed below.

From determinism and control to chaos and self-organization in physical sciences.

Studies on complex systems came from the effort to identify the limitations in the reductionist explanations of all phenomena, in terms of fundamental physics laws. Since Descartes, Newton, and other founders of the modern sciences, “the ideal of reductionism in science” (Kauffman, 1996, p. 16) was prevalent until the beginning of the twentieth century. Newtonian mechanics implied an image of a clockwork universe. Its implications became the source of hope for complete prediction for scholars such as Pierre Simon Laplace, a prominent physicist and mathematician at the time. He specifically asserted that using Newton’s law we could, in principle, predict the future of the universe, given the initial condition of each particle (Laplace, 1814). This dream of perfect prediction was shown unreachable within 100 years, by Werner Heisenberg’s uncertainty principle in quantum theory and Henri Poincaré’s dynamical systems theory (Kauffman, 1996; Mitchell, 2009). Emphasizing the impossibility of complete prediction, Poincaré (1908) stated:

If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon has been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomenon. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible. (p. 68)
Poincaré illustrated the impossibility of perfect prediction by showing how Newton’s differential equations in his model of the solar system work if one considers only two bodies in the system. He illustrated that predicting the future paths of three bodies, considering their mutual interactions, is not a solvable problem. He pointed to the fact that a slight change in the bodies’ initial position would cause orbits with drastically different paths (Poincaré, 1890). The illustrations of the shortcomings of Newtonian mechanics, therefore, discredited the assumptions of the simplicity of nature and the linear cause and effect relationships, i.e., small changes or actions result in small effects, and large changes lead to large effects. Chaos theory, as a proceeding of this view, was mostly developed through the studies of physicists and mathematicians, such as Edward Lorenz in the 1960s, on nonlinear systems. Chaos theory emphasizes the sensitivity of systems to initial conditions and nonlinearity of causal relations, metaphorically explained as the flap of a butterfly in Brazil can cause a tornado in Texas (Doll, 2008; Mitchell, 2009). Dynamical systems and chaos theory were not merely an attempt to show the disorders in the universe, but also provided explanations, mostly mathematical, for chaotic systems that Newtonian mechanics could not. Their findings led to a set of common properties, such as Feigenbaum’s constant (Feigenbaum, 1979), in chaotic systems that contributed to the prediction of macro-level behaviours in systems, such as weather systems, electrical power systems, and the heart (Mitchell, 2009).

In the late 1940s, a strand of research on information and communication theories assessed the storage, transmission, and process of information within systems, using the dynamical systems approach. Claude E. Shannon’s mathematical theory of communication in 1947 had a significant contribution to this area. Shannon and Weaver (1949) used the notions of noise and redundancy (common elements) in relation to each other to address the viability of recovering signals transmitted through communication channels. This strand of research and the proceeding studies on entropy in thermodynamics contributed to understanding complex systems (e.g., Ebeling, 1993), which is explained later in this section.

The research on computation also had a remarkable contribution to understanding the processing of information in complex systems, including living systems. Grounded in the work on symbolic logic and Alan Turing’s work in the 1930s, the concept of automata (a Greek word meaning self-acting) was developed to characterize complex systems. This concept proposed discretizing states and temporal processes to address the logical principles underlying
information processing within systems (Alhadeff-Jones, 2008; Yu et al., 2005). Cybernetics was another significant movement, which was grounded in the development of information and automata theory and was expanded through the work of scholars from different disciplines such as Norbert Wiener, a mathematician and philosopher, and W. Ross Ashby, a psychiatrist. Cybernetics used the notion of feedback, connecting it to the concept of information, to explain the adaptation process in complex systems and to offer a framework to describe how organisms use and exchange information to control their own behaviour (Alhadeff-Jones, 2008).

The notion of self-organization points to the emergence of a new global order in a system resulting from internal fluctuations that happen in the system’s elements and their interactions. This process is distributed over all the agents and no single agent or external factor controls it (Heylighen, 2008). This concept has been explored and explained using various terms in different fields, including social sciences (Self-referentiality in systems theory (Luhmann, 1982)) and biology (Autopoietic systems (Maturana & Varela, 1980)). In physical sciences, mainly in the research on dynamical systems and thermodynamics, this notion was significantly addressed in the work of Ilya Prigogine on dissipative structures and non-equilibrium systems in the 1970s (Mitchell, 2009; Prigogine & Stengers, 1984). In short, a dissipative structure sustains through the exchange of energy, matter and information with its environment, and in the case of internal fluctuations, it could approach a far-from-equilibrium state. In this condition, nonlinear relationships take over the structure and the system become extremely sensitive to external stimuli. A small change could affect the system significantly and lead to its reorganization (Prigogine & Stengers, 1984). An example of such a process is convection in a heated liquid, in which the heat energy is transferred by the movement of a bulk of molecules (non-equilibrium state) after a certain increase in the liquid temperature, rather than being conducted from molecule to neighbouring molecules without their significant repositioning (equilibrium state) (Sundarasaradula & Hasan, 2005).

A historical review of the development of research on complex systems in “mathematics and physical sciences” is provided in the first row of Figure 1.

**Exploration of life and evolution and the development of complex adaptive systems.** The studies in mathematical and physical sciences on complex phenomena paralleled the research on life and evolution that was influenced by evolutionary biology (see “life sciences” in
Figure 1, first row). Warren McCulloch and Walter Pitts’s (1943) work on neural networks, was one of the early contributions to this trend. Informed by the automata theory, they developed computational models of neural systems to explain the biological processes in the brain as neural networks. These models were later applied to artificial intelligence and machine learning (Schmidhuber, 2015). Through this movement, the concepts in evolutionary biology were re-examined by statistical models (e.g., Raup et al., 1973). New connections between the evolution of living systems and the emergence of cognition were also studied in the work of Gregory Bateson (1972), and in the proceeding research on autopoiesis. In the 1970s, Humberto Maturana and Francisco Varela originally used this notion to refer to the reproduction and self-maintaining of living cells. In their later work, they described living systems as cognitive systems, and living “as a process of cognition.” They explained a cognitive system as “a system whose organization defines a domain of interactions in which it can act with relevance to the maintenance of itself” (Maturana & Varela, 1980, p. 13).

The concept of complex adaptive systems was developed in the 1980s out of the collaboration of researchers focused on the evaluation of complex systems in physical, biological and social systems. Among others, the genetic algorithm developed by John Holland in the 1970s (see Holland & Reitman, 1977), was one of the theories that contributed to this trend (Alhadeff-Jones, 2008). The genetic algorithm, which was shaped based on the work on biological evolution, aimed to model and solve optimization problems and led to the definition of evolutionary computation (Page, 2016).

**Systems theory in human and social sciences.** Considerable studies on the complexity of social systems were mostly initiated in the fields of economics, management, and psychology (see “Social Sciences” in Figure 1, first row). One of the early contributions was Herbert Simon’s work on decision making processes in organizations (Simon, 1947), and on “human problem solving” and “human thought” in collaboration with Allen Newell. Their work explored the complexity of thinking and problem-solving processes through computational modeling (see Newell & Simon, 1959). His work also contributed to the research on artificial intelligence and later, along with the work of other scholars such as Bateson and Edgar Morin, to the development of a constructivist view of complexity (Le Moigne, 2001). In his work, “architecture of complexity”, Simon (1962) elaborated on the notion of complexity by describing systems as hierarchic: each complex system is composed of interrelated entities, which
themselves are complex and consisting of complex parts at a lower level of organization. Similarly, he described social systems as “parts-within-parts” structures: “almost all societies have elementary units called families, which may be grouped into villages or tribes, and these into larger groupings, and so on” (Simon, 1962, p. 469), each of which are complex at a different level of organization.

Talcott Parsons is another notable scholar who pursued pioneering research on social systems. Parsons’s social action theory, described in “the structure of social action” (Parsons, 1937), is considered as one of the first systemic and generalizable theories of social systems. In his systems theory, Parsons (1951) elaborated on social action as emerging from the interactions of personality, and cultural and social systems. As Dillon (2009) explains, for Parsons, “individual behaviour cannot be understood in terms of individuals’ internal processes (what psychologists study), but in the context of the social structures and the cultural values that invariably constrain the individual and determine all social action” (p. 156). He proposed a general functional-analytic model of social systems, in which all social collectives should perform to be stable and individual entities are evaluated based on their function in maintaining the system's equilibrium or social order (Dillon, 2009). This emphasis on systems’ stability and tendency to return to an equilibrium (the norm) was, however, challenged later by complexity perspectives that describe complex systems as performing in far-from-equilibrium and in constant change (e.g., Walby, 2007).

Niklas Luhmann continued developing systems theory from the perspective of autopoiesis, since the 1970s. Luhmann argued that “social systems are self-referential. As such, they can be best viewed as autopoietic systems” (Luhmann, 1982, p. 131), which produce and reproduce their own parts and structure. He evaluated the society as consisting of various autopoietic systems, including legal, scientific, economic and educational systems, which sustain in a complex environment (Luhmann, 1982). It is important to note that Luhmann did not refer to the tangible elements of systems, but to the intangibles, such as communications. Mattheis (2012) elaborated:

Each social system consists of countless meaningful communications. Moreover, society is only possible where communication is possible… Communication can be considered as the basic unit of observation for the assessment of the operations of social systems…
Communication is an ongoing, without interrupting sustained operation, which reproduces itself. (Mattheis, 2012, p. 628)

It is, therefore, through the consideration of constant interrelations and interactions of communication operations within and between social systems that one can make sense of social systems as evolving and not as stable structures (Luhmann, 1982). Mesjasz (2010) highlighted Luhmann’s approach to the role of the conscious observer in comprehending the meanings of social systems. From Luhmann’s view, the observer is never indifferent and becomes a participant of the social system. This connects Luhmann’s perspectives to soft systems thinking (Checkland, 1981). In contrast to hard approaches that consider systems as existing in the outside world, in soft systems thinking “systemicity is shifted from the world to the process of inquiry into the world” (Checkland & Haynes, 1994, p. 193).

Mesjasz (2010) also considered linguistic approaches to the interpretation of complex social systems, proposing that complex systems studies would be the sources of metaphors and analogies in social sciences. As Tsoukas and Hatch (2001) discussed, complex systems concepts, such as chaos, were metaphors that could give us a new lens to see new phenomena and interdependence, and expand our possibilities for thought and action (Morgan, 1997; Rorty, 1989). From this perspective, complexity may not be intrinsic to systems but helps us organize our thinking about social phenomena and our interactions with these systems, and make sense of events in context and of their interconnections over time (Tsoukas & Hatch, 2001).

**Complexity as an epistemological problem, a dialogue between social and natural sciences.** Edgar Morin, one of the contemporary complexity thinkers, challenged contemporary disciplinary considerations and interdisciplinary approaches, which were limited to incorporating methods of one discipline to inform another, pointing to the disjunctions in the organization of knowledge. He presented a transdisciplinary approach that involved a dialogue between social and natural sciences (Montuori, 2008). Morin described an epistemic loop in which knowledge was produced in cyclic processes, rather than by linear accumulation, among seemingly fragmented fields of inquiry (Alhadeff-Jones, 2008). This approach took roots in Morin’s assertion on complexity not to be “restricted” to disciplinary and interdisciplinary discussions (on certain “laws” in systems considered as complex), but to be thought of “epistemologically”. He posited that “restricted complexity made possible important advances in formalization, in the
possibilities of modeling, which themselves favor interdisciplinary potentialities”. However, what complexity offers should not be narrowed down to this approach:

One still remains within the epistemology of classical science. When one searches for the ‘laws of complexity’, one still attaches complexity as a kind of wagon behind the truth locomotive, that which produces laws. A hybrid was formed between the principles of traditional science and the advances towards its hereafter. Actually, one avoids the fundamental problem of complexity which is epistemological, cognitive, paradigmatic. To some extent, one recognizes complexity, but by decomplexifying it. (Morin, 2008, p. 6)

Morin introduced the notion of generalized complexity that “not only concerns all fields, but also relates to our knowledge as human beings, individuals, persons, and citizens” (p. 21). From this perspective, he called for a deep reform of our ways of knowing and thinking and supporting this reform through education. His principles for such education included making sense of human knowledge with its cerebral, intellectual and cultural attributes, its development process, and its potentials for illusion and error (Morin, 2001). The educational project not only should support distinctions, as in disciplinary analysis, but also should encourage reconnecting parts to “grasp subjects within their context, their complexity, [and] their totality” (Morin, 2001, p. 1). From another perspective, it should be attentive to teaching the “human condition” that is human beings are biological, psychological, social and historical, and to how to face uncertainties associated with sciences and history as well as everyday life (Morin, 2001, 2008).

The reviewed moments in the development of complexity research, offer frames for disciplinary and cross-disciplinary inquiry and, from a broader perspective, a different sensibility of knowledge and learning that entail a shift from linear, deterministic views to the appreciation of divergent and emergent approaches.

The following sections explore the contributions of complexity perspectives to the learning sciences in two ways: First, the research on using complexity as a frame to study learning systems, and to support the emergence of individual and collective insights in such systems, and second, the design studies that attempt to help students develop a better understanding of real-world complex phenomena.
**Complexity as a frame to make sense of knowledge and learning**

The mathematical and qualitative views to complexity discussed above have developed pathways to making sense of knowledge and learning from a complexity perspective. A number of significant scholarly works from the mid-20th century have contributed to bringing complexity perspectives to educational research. They include the descriptive scholarly discussions of knowledge and learning and the pragmatic views on structuring learning systems from complexity perspectives.

**Complexity and the discussions of knowledge, knowers and learning.** Acknowledging the compatibility of recent educational research with complexity research, Davis and Sumara (2006) argued that educational research has a considerable contribution in elaborating concepts in complexity research. Complexity theory’s “insights into the nature of continuity and change” (Mason, 2008, p. 2) in complex systems indeed hint to the characteristics of learning and the goals of education. “Some key principles of complexity are prominently represented within such theoretical perspectives as radical constructivism, situated learning, enactivism, and some versions of social constructivism” (Davis & Simmt, 2003, p. 138). Addressing the notions of knowledge and learning, various related theoretical perspectives, have similar and compatible approaches to complexity research, embodying concepts such as emergence, adaptability and change, nonlinearity, uncertainty, feedback and self-organization (Jacobson et al., 2019; Shihui & Shaodong, 2012). Davis and Simmt (2003), however, elaborated that these theoretical frames addressed learning as emergent phenomena at different specific levels. For example, radical constructivism (von Glasersfeld, 1995) is concerned with the individual’s interpretations of the world whereas social constructivist perspectives explore collective phenomena such as “the emergence of cultural norms” (Ernest, 1991, p. 142, as cited in Davis & Simmt, 2003). The second row of the historical map (Figure 1), provides a glimpse of such approaches to knowledge and learning that are compatible with complexity views (adapted partially from Davis and Sumara (2006), and complemented by insights from Greeno et al. (1996), Kim and Reeves (2007), and Salomon and Perkins (1998)).

Complexity theory could, however, provide a frame to read across diverse phenomena described by different learning theories considering the different levels of learning as nested systems. Davis and Simmt (2003) and Davis and Sumara (2006) have also developed a
pragmatic approach to using complexity principles to transform learning systems at different levels. These complexity-informed conceptual and pragmatic views are explored further after a brief review of their background in educational research.

The explicit use of complexity discussions in the field of education can be traced back to the mid-20th century (e.g., Jensen & Parsons, 1959; see Figure 1, fourth row). Elton and Laurillard (1979) discussed the shortcomings of theoretical work in education in influencing the practice, considering the complexity of issues in education and studying these issues. They questioned using reductionist approaches influenced by physical sciences for investigating highly interconnected problems in learning and teaching. This work specifically challenged cause-effect explanations in attempt to evaluate and control learning situations and argued for a shift towards making sense of relations within the highly interwoven teaching and learning situations.

Sawada and Caley’s (1985) work on introducing “dissipative structures as new metaphors for becoming in education” was prominent in making an explicit analogy between the conditions of self-organizing (complex) systems (Prigogine & Stengers, 1984) and those of systems with educational goals. They argued for standing away from the prominent tendency to create “normal” and controllable systems, which would barely support change for participants, and creating learning environments that would embrace deviation and support far-from-equilibrium states. Referring to the complexity theory and the study of self-organization (Prigogine, 1980; Prigogine & Stengers, 1984), Doll (1986, 1989) argued that developing a curriculum with these perspectives could support students to rethink their habitual ways of approaching problems through communication and cooperation. Doll (1986) pointed out how education and curriculum development had been strongly influenced by Newtonian “God's-eye view of the universe, seeing it as static, uniform, and externally controlled” (p. 12). This approach is far from more complex views, pioneered by Einstein, Heisenberg, and Piaget, that see the world as an open system that is “filled with change, randomness, and indeterminacy” (Doll, 1986, p. 13) and the reality as complex, temporal and diverse (Prigogine & Stengers, 1984). Doll proposed an educational model that requires educators to recognize that understanding and development are not instantaneous and linear but happen cumulatively through the consideration of multiple arguments and reflections.
The discussed exceptional contributions, however, were not effectively followed for the next two decades. More work on the direct use of complexity in studying the dynamics of learning and proposing guidelines for teaching and structuring learning environments has unfolded only in the past 20 years. Unlike how theories of knowledge and learning represented some principles of complexity only at a particular level, i.e., individual or collective, Davis and Simmt (2003) described complexity as “concerned with a range of nested learning systems, which includes the co-implicated processes of individual sense-making and collective knowledge generation” (p. 142). They also offered a pragmatic approach on the activities of learning systems. This approach focused on the conditions for an “expanded possibility that comes about when differentiated agents, who operate at a local level with local rules, come together in manners that complement and amplify existent possibilities while opening up others in the space of joint action” (Davis & Simmt, 2003, p. 147). Based on the properties of emergent systems, the authors suggested the necessary but insufficient conditions for the emergence of learning systems, including internal diversity, redundancy, decentralized control, and neighbour interactions. This pragmatic view could also be inferred from Sawada and Caley (1985) and Doll (1986)’s assertion on creating structures that support multiplicity and far-from-equilibrium states to open the space for knowing and becoming. Elaborating this practical approach, Davis and Sumara (2006) challenged using descriptive views of knowledge and learning, such as constructivist theories or the critical theory, as theories of education, or as a means to frame the practices of teaching or schooling. From another point of view, they emphasized the transdisciplinary nature of education, taking into account various issues such as individual and collective learning, various areas of inquiry including psychology and sociology, and different subject matters such as mathematics. Characterizing education as transdisciplinary and pragmatic, they argued for incorporating complexity thinking as a “powerful means to pull together a diversity of disciplines and discourses while enabling researchers and practitioners to deal with the practical aspects of the formal educational project” (p. 130).

From complexity perspective, knowledge production is an ever-continuing endeavour of expanding the possible interactions among diverse ideas and interpretations. In a similar vein, an education for a complex world should not be perceived in terms of “top-down, ends-driven structures”, but as “oriented toward the as-yet unimagined” (Davis & Sumara, 2006, p. 135). Osberg and Biesta (2007) also proposed the use of complexity to promote an “emergentist
epistemology.” This view does not hold the prevalent assumptions of education as “a tool for planned enculturation” rooted in a representational epistemology. The latter view sees the curriculum as a means for transferring what currently exists or is believed, and aims to “replicate in the learner the knowledge of some preconceived ‘way of being’” (Osberg & Biesta, 2007, p. 35). This approach had been challenged by contemporary epistemologies such as constructivism and poststructuralism, which posit that knowledge and meaning “emerge,” and come to existence only through our participation in the world (Osberg & Biesta, 2007). They argued that such “emergentist epistemology” could “free education from the logic of planned enculturation… [and attempts of] directing the subjectivity of others towards some cultural end” (p. 36). From an emergentist position, there is no assumption about the starting and planned ending point for human subjectivity. “The question of what it means to be a human subject” (p. 36) is, itself, what that should be explored through interacting with others in the systems we are part of. In this sense, a curricular space is a “space of emergence” for the individuals to make sense of the constraints they face through participation, and to emerge as singular beings capable of making a unique contribution. Put differently, an emergentist approach promotes a conception of education that embraces and opens the space for the dynamic re-creation of cultures and ways of being, rather than the reproduction of certain cultural ideals (Osberg & Biesta, 2007).

Computational modeling of systems of learning. Besides the reviewed qualitative complexity perspectives, a body of research in the learning sciences, developed in the past years, explores the possibilities of using mathematical approaches to analyzing complex systems to model systems of learning. This line of research could be considered as aiming to more directly use tools and methods of studying complex natural systems for simulating social systems. The early pursuit of such approaches could be found in cyberneticists’ mathematization of social systems and the initial work of Herbert Simon on human problem solving (see Simon, 1947). Jacobson and Wilensky (2006) addressed the potentials of computational modeling of systems of learning in informing educational research and theory. They suggested that the use of computational modeling could extend the research in learning sciences by providing tools for the evaluation of “micro- and macro-levels of cognitive, learning, and educational systems, such as the evolution of cognitive representational networks, design experiments of technology interventions in classrooms, and social network analysis of collaborative interactions patterns” (p. 28-29). Manu Kapur and his colleagues’ studies on modeling the processes of problem
solving and systems of learning demonstrate the possible implementations of this approach. Kapur et al. (2005) created an analogy between the evolution process in complex adaptive systems and the mechanisms of problem solving. They discussed that “a group of people collaborating to solve a problem can be seen as a complex adaptive system, and evolution entails how the group interacts to solve a problem and how this interaction develops and changes over time” (p. 253). In a study of a computer-supported text-based collaboration of 60 junior high school students, randomized into 20 groups to work on problems in Newtonian Kinematics, they coded segments of group problem solving interactions, using Quantitative Content Analysis (QCA). Based on a macro-level analysis of converging group discussions to an ideal solution, they highlighted a temporal understanding of the emergence of structures and solutions, which contrasts treating problem solving as a linear, stepwise activity. Kapur et al. (2008) also explored students’ problem solving interactions, considering how micro-level dynamics resulted in macro-level group performance, which was defined by “problem solving convergence” towards the solution. The interactions within the groups were mathematically modeled. “Accordingly, each members’ contribution was conceptualized as a simple rule (or a conditional action) that moved the group’s solution toward (positive contribution) or away (negative contribution) from a correct solution, or maintained the status quo” (Jacobson et al., 2016, p. 214). Their analysis showed the extended effect of the early contributions, both positive and negative, on the group problem solving convergence. As they asserted, “interestingly, sensitivity to early exchange exhibited by CSCL groups in …[this] study seems analogous to sensitivity to initial conditions exhibited by many complex adaptive systems” (Kapur et al., 2008, p. 63). Reviewing this study, Jacobson et al. (2016) suggested that “relatively simple rules … could be used to model micro-level interactions to examine how groups self-organize into convergent or divergent problem-solving trajectories, the temporal evolution of these trajectories, and the predictive effects of settling into such trajectories … on eventual group performance” (p. 214).

This discussion, therefore, suggests that different research methods in education can contribute to the understanding of education systems from the complexity perspective. Jacobson et al. (2019) discuss the potentials of quantitative, qualitative and modeling tools in this vein, arguing that such tools could be more suitable for explaining complexity views of education than the most widely used quantitative and qualitative methods. Quantitative methods such as differential equations and statistical modeling are cited to be linear tools “breaking a system into
its components or parts, studying the parts individually, and then adding the parts together to form the whole”, which is incompatible with emergent, nonlinear phenomena (p. 114). Both qualitative and quantitative methods are, however, limited in that they describe “what has already emerged” (p. 114), rather than discussing other possible trajectories that “could have unfolded” (p. 114). A third category of methods, namely computer modeling tools, have been developed to study nonlinear dynamics in complex systems which can complement existing qualitative and quantitative methods. Of note in these modeling tools are Agent-Based Modeling (ABM) and equation-based modeling (EBM), the former aiming to express the behaviour of entities or agents through time, and the latter aiming to formalize equations to represent how entities are related and how aggregate behaviours emerge.

Some scholars have, however, challenged extensive reliance on mathematical and computational modeling of human interactions. Davis and Sumara (2006) argued that although such hard approaches to complexity could be of some use in informing educators about individual learning and group dynamics, they would be of limited value in understanding the phenomena of interest in education, such as classroom interactions that constantly evolve. They also discussed that the researchers with mathematical modeling approaches did not consider their own roles in the human systems they studied and their evolution.

*Complexity as a subject matter: Design perspectives for students’ understanding of complex phenomena*

Along with the development of research on complex systems, there have been attempts to create technologies that support experts and researchers in different fields to make sense of such systems. Examples of the developed computational tools include cellular automata, network modeling and Monte Carlo simulations. The development of analytic tools for understanding complex systems in scientific and professional contexts has encouraged projects on developing methods and technologies for learners. This orientation has led to the design of complex systems curricula for K-12 students.

*Students’ conceptions of complex systems.* The focus on designing environments to enhance students’ understanding, also prompted a body of research on the nature of students’ initial conceptions of complexity. This specifically included studies that compared novices’ conceptions of the qualities of complex systems and experts’ understanding. Wilensky and
Resnick (1999) argued that making sense of complex systems would entail a fundamental shift from linear, deterministic patterns of scientific thinking to nonlinear and probabilistic approaches to complex phenomena. The linear patterns of thinking have been observed in several studies on students’ and novices’ conceptions of complex phenomena. Resnick (1996) and Jacobson (2001) showed that students tend to describe the collective behaviour of systems as controlled by a "centralized entity" within systems, assuming them as linear and predictable. Perkins and Grotzer (2005) posited that students often interpreted complex phenomena with causal models and focused on the instant effects of agents’ actions neglecting their extended effect on the system. Sweeney and Sterman’s (2007) study on children’s “intuitive models” of natural and social complex systems showed that recognizing interacting patterns, feedback, and delayed effects of changes in systems were challenging for students. Students applied “open loop or one-way causal thinking” (p. 285) and reasoned only about snapshots of elements’ actions. This study also discussed that teachers, as well, had difficulties in reasoning about dynamics of systems, specifically in talking about long-term systems’ patterns. This suggested that limitations in understanding complex systems were not a matter of age.

Chi and her colleagues conducted another line of research on children’s conceptions of complex disciplinary problems since the 1990s (e.g., Chi, 1992; Chi et al., 2012; Chi & Slotta, 1993). Chi and Slotta (1993) attributed the observed differences between novices’ and experts’ understanding to “ontological categories” associated with one's conceptions. In this view, novices’ difficulty in reasoning, in the context of physics, is rooted in thinking within the category of “matter” rather than “processes,” and “direct processes” rather than “emergent processes”. This difficulty necessitates a conceptual change in novices to come to a better understanding, which is a challenging process as ontological categories are “distinct, stable and constraining” (Chi & Slotta, 1993, p.6). Several scholars (Sengupta & Wilensky, 2009; Gupta et al, 2010), however, challenged this static view of ontological knowledge. Analyzing people’s everyday thinking and language use, Gupta et al. (2010) argued that people constantly moved across the matter and processes ontological categories, using common metaphors. The authors also found that both experts and novices blended ontological categories in their reasoning about scientific concepts and argued how it is both “productive and essential” (p. 12). They asserted that their evidence “points towards a dynamic picture where our ontological knowledge is flexible and ideas in the world and ontological categories are multiply connected. Theoretically,
this suggests that our conceptual knowledge organization is likely to be network-like rather than hierarchical” (p. 27).

From an instructional point of view, this dynamic model proposes using students’ various resources for reasoning about scientific concepts. This involves helping students pay attention to different viewpoints and become aware of the affordances and limitations of their own resources and descriptions (Gupta et al., 2010). Wilensky and his colleagues, similarly moving away from the categorical view (e.g., Levy & Wilensky, 2008; Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999), attributed students’ challenges in understanding complex phenomena to “slippage between levels” (Wilensky & Resnick, 1999, p. 4), i.e., confusing the agents’ level and the emergent level in complex systems. They argued that even experts might find understanding emergent patterns challenging and counterintuitive (Sengupta & Wilensky, 2009). They, however, suggested that people (even young learners) have the conceptual resources to make sense of connections between levels, specifically when starting the analysis at the agent level. Extending this strand of research, Sengupta and Wilensky (2009) argued that carefully designed interventions could support novices’ understanding of emergent phenomena through “bootstrapping, rather than discarding their existing repertoire of intuitive knowledge” (p. 21). Scholars with similar views continued exploring design approaches to support learners.

**Design approaches for supporting students’ understanding of complex systems.**

Reviewing the literature, one finds different pedagogical views and the use and design of various tools and activities for supporting students’ understanding of complexity (Yoon & Hmelo-Silver, 2017). A prevalent focus in designing learning environments, however, has been on students’ using and creating models of complex systems. The centrality of computational modeling and simulation tools could be observed in a considerable number of studies, specifically in the pioneering studies on developing students’ conceptions of complex phenomena (e.g., Brandes & Wilensky, 1991; Klopfer, 2003; Resnick, 1994; Wilensky & Resnick, 1999).

Mostly used in higher education, the system dynamics modeling tools are instances of computational technologies that help students evaluate aggregate behaviours over time, specifically in industrial, social and ecological complex systems (Forrester, 1990; Senge, 2006). System dynamics modeling uses differential (or integral) equations, using different sources such as statistical data or expert opinion (Sterman, 2001), to explain global structural dependencies
and predict systems’ macro-level patterns (Borshchev & Filippov, 2004). Such tools are also
categorized as equation-based modeling (EBM) tools, as they rely on algebraic or partial
differential equations to represent the relationship between agents and their aggregate behaviour
over time (Jacobson et al., 2019). Another major thread in the design and use of computational
tools is agent-based modeling (ABM). ABM does not describe the macro-level patterns in a
system but defines the rules at the level of individual agents. The global behaviours consequently
emerge from the actions and interactions of a large number of agents. The purpose of ABM is,
therefore, to develop an understanding of how behaviours and interactions at a lower level could
generate macro-level behaviours (Goldstone & Wilensky, 2008; Page, 2012).

StarLogo (Resnick, 1991) and NetLogo (Wilensky, 1999) are modeling platforms that are
developed based on the agent-based modeling approach and have been used to support K-12
students’ understanding of complex systems (see Figure 1, third row, for an overview on the
mainstream of research in this area). Wilensky and Resnick (1999) studied three cases of
students’ modeling activities with StarLogo to make sense of the behaviour of slime-mold cells,
the process of gas distribution in a box, and the patterns in a predator-prey ecosystem. They used
the notion of “emergent levels” to indicate how unexpected patterns could arise from the
interactions in lower system levels. As discussed above, they described level confusion as the
source of “people’s deep misunderstandings about patterns and phenomena in the world” (p. 3).
To evaluate and develop high school students’ understanding of the concept of levels in systems,
they designed activities that mainly relied on building models of systems from scratch or
modifying pre-constructed models. Their analysis suggested that through using and creating
models, students iteratively examined their conceptions about the overall effect of changes in the
initial conditions and the local rules at the level of individual elements. The researchers also
pointed to students’ personal connection with the digital creatures through which they created
their models, and how this made systems ideas more accessible to them. According to them, this
is specifically useful for those students who are not trained with advanced mathematics required
for describing emergent oscillations in population, or with modeling tools that rely on aggregate
patterns (e.g., in the systems dynamics approach). This view of the affordances of computational
agent-based modeling tools, mainly StarLogo and NetLogo, for developing students’
understanding of complexity has been the basis of a line of study in the learning sciences. In a
study on developing students’ understanding of natural selection, Dickes and Sengupta (2013)
also argued that agent-based reasoning was more accessible to young students than the prevalent “aggregate-level formalism” used in science classrooms, as it capitalizes on children’s intuitions about “their own bodies, perceptions, decisions and actions” (DiSessa, 2001; Levy & Wilensky, 2008; Papert, 1980). Similarly, Basu et al. (2015) discuss the potentials of multi-agent-based modeling as pedagogical tools that can scaffold students’ learning of challenging topics, such as ecological systems. Emphasizing the potential of multi-agent models in understanding different levels in complex systems, they design a NetLogo agent-based simulation whereby five species (two plants and three animals) in the desert ecosystem interact with each other and with the environment. They show that by building a visual qualitative causal model, students can better construct explanations of how aggregate-level phenomena emerge (e.g., the population growth of certain species) from agent-level relationships.

Some studies expanded modeling complex systems to include participatory activities. In these studies, students took the role of systems’ agents and followed the local rules for their actions (e.g., Colella, 2000; Dickes et al., 2016; Wilensky & Stroup, 2002). Colella (2000) conducted a participatory simulation game of disease spread in a high school classroom. Using wearable computers, called “Thinking Tags” that could communicate, each student was transformed into a potential carrier of a virus. Individuals could be infected as the result of their interactions with one another. Through their immersive experience with an epidemic, students collaboratively investigated the possible dynamics by varying their own behaviour, collecting data and observing the effect of alterations in their behaviour on the simulation outcome. Colella (2000) underscored the significance of “deploying the phenomena in the students’ own interpersonal space” (p. 493), rather than envisioning the transformation of students’ experiences through their individual interactions with a single tool (e.g., computational modeling tools). She also asserted that students’ discussions on the underlying rules and the emergent dynamics helped them appreciate the importance of exploring every participant’s personal experience to make meaning out of their collaborative activities and to understand the system under study. Levy and Wilensky (2008) also used participatory activities to engage students with complex phenomena in the context of simulating everyday situations, such as students’ same-sex grouping in playgrounds, and the spread of a rumour in a school. Through these, students reasoned about the emergent patterns while participating in simulation activities. They suggested that students would benefit from a complementary approach, which includes both agent-based reasoning (i.e.,
reasoning about the actions and interactions of individual elements) and aggregate reasoning (i.e., explaining how macro-level patterns change over time). More examples of the pioneering work on the use of participatory simulations are provided in the third row of Figure 1.

More recent studies have also focused on participatory learning environments to investigate multiple aspects of learning that include students’ individual and collective understanding, and the tools that mediate their understanding. Langbeheim and Levy (2019) discuss the benefits of using a participatory simulation design, whereby students take the role of a particle floating in a liquid and interacting with other particles, over conventional simulations where students configure system characteristics such as temperature using sliders to see how the system would behave. They argue that such participatory methods afford significantly deeper learning and joyful engagement for students. This happens through lowering the cognitive load on the learners in learning complex phenomena, as they do not have to navigate a large number of interrelated elements and observe the emergent system behaviour at the same time. Instead, they could be an agent of the system and observe those interactions themselves. Such “role-play” of an element of the system can also increase the emotional engagement of students in learning about complex systems (p. 68). Danish (2014) emphasized exploring the nuances of students’ interactions with one another and with multiple tools while engaging them in various activities, besides considering individual students’ cognitive engagement with a single tool. He discussed that the work on comparing novices’ and experts’ conceptions and using modeling platforms to enrich the understanding of complex systems provided valuable insights. They included how making sense of systems concepts can support students’ understanding of the content (Jacobson & Wilensky, 2006), and their transfer of understanding (Goldstone & Wilensky, 2008). He, however, maintained that these studies have been based on a cognitive view and consequently more concerned with the individual aspect of learning “rather than viewing the learning environment itself as a system” (Danish, 2014, p. 101). Dickes et al. (2016) also argued for the use of different forms of activities, including embodied modeling, agent-based modeling and representational practices. They underscored the “egocentric” form of embodiment through which “one’s body is imagined as a biological agent’s body” (p. 737). The researchers, therefore, engaged students in a collaborative re-enactment of an ecosystem, in which each student was encouraged to “think like an agent” (p. 745) of the ecosystems as well as other relevant interacting agents. Dickes et al. (2016) asserted that students’ adoption of multiple perspectives
could promote their understanding of survival mechanisms in the systems. They also underscored how the proceeding creation of agent-based models using NetLogo helped students build on their embodied experiences and make a better sense of how the interaction of diverse agents leads to emergent behaviours of the system.

There is also a changing trend in the learning content in the design of studies in this theme. Earlier studies had a greater focus on complex issues from biology or physics. More recent studies, however, increasingly include complex socio-scientific issues such as climate change, as well as social and political complex issues (e.g., Markauskaite et al., 2020; Hostetler et al., 2018; Pallant & Lee, 2015; Visintainer & Linn, 2015). Markauskaite et al. (2020) conducted a study on the potentials of model-based learning of the complex socio-scientific issue of climate change. They argue that socio-scientific topics involve “a complex relationship between social, political and scientific questions" and as such are prone to various interpretations which are experiential and perspective-dependent. In their modeling-based design of high school students’ learning about carbon cycles, they demonstrated that students show diverse ways reasoning when interacting with agent-based models of complex phenomena. They discussed that students ground their understanding about complex issues when working with models at a continuum of five levels: direct observation, straight abstraction, generalization, conceptualization and extension. These five ways correspond to a level of understanding originating with the natural perception of the existing system and extending to a complex cognitive ability “to see the world in a particular way and make diverse kinds of inferences and connections” (p. 71). Hostetler et al., (2018) further expand the agent-based modeling efforts to the domain of social studies learning where students learn about ethnocentrism and racial segregation as emergent issues. Importantly, they posit that teachers avoid important political and social discussions on complex issues such as race, ethnicity, sexuality, gender and income inequality, as navigating the pedagogical challenges with their students in an increasingly polarized political world could be overwhelming for them. They designed an ABM simulation of ethnographic patterns emerging through time and a one-dot map of ethno-racial distribution on the US map to study the affordances of computer-based modeling tools in helping students learn about complex social and political issues. They argued that agent-based modeling can serve as a method for teachers to engage in deep conversations about critical issues such as race, ethnicity and power, by projecting themselves as different types of agents in a simulated environment,
thus not having to reveal their personal views to such polarized matters. From learners’ point of view, the agent-based modeling tools have the benefit of having agents as transitional objects, meaning they enable students to project their identities on the agents, while also using agents to project the identities of both the “self” and the “other”. The first aspect means that students use their own narratives and experiences to reason about the behaviour of the agent while keeping a distance from the agent, not having to situate the social-political phenomena in their own personal lives. The second aspect further enables students to consider the perspectives of both agent types in exploring and interpreting the simulation: themselves, and others such as people of a different ethnical background. In that sense, they are more likely to engage in critical discussions involving various aspects and interpretations about the complex socio-political issue under study (Hostetler et al., 2018).

There has also been growing attention to the potentials of using games as models of complex systems in supporting students’ understanding of qualities of systems and engaging with socio-scientific phenomena (Clark et al., 2015; Gee & Tran, 2016; Gee, 2008; Junior et al., 2020; Zimmerman, 2013). Games are rule-based but complex and dynamic as players decide their moves and interact within the structure (Gee, 2008). Considering games as dynamic systems, their level of complexity determines the possibilities and mechanisms of game play, through which players’ choices and actions result in the overall outcomes. In other words, the complexity of a game contributes to the extent to which player actions are meaningfully connected to system outcomes (Salen & Zimmerman, 2003). Scholarly work on using game design, in particular, has been developing with the goal of helping learners make sense of everyday life situations as well as complex social and environmental phenomena (Kim & Bastani, 2017; Parekh et al., 2021; Walsh, 2010). Game design entails deciding about rules that underlie the actions and interactions of players as agents of the game’s system. It, therefore, engages students with creating the space for participation, interaction and strategizing that make the play possible and meaningful (Salen-Tekinbaş et al., 2014; Walsh, 2010). Through iterative cycles of design, decision-making, and problem solving, learners not only craft game rules, but also make sense of games as complex dynamic systems with emergent patterns. They develop this understanding by experiencing how games’ meaning emerges in social settings, through the interactions among players, game elements and rules (Bastani & Kim, 2020; Salen, 2007). In this developing strand of research, some studies point to the value of computational simulations and
playing and designing digital games, but argue for using board game design as a more accessible practice that has a significant potential in supporting learners’ understanding of complex systems in their familiar social settings. Kim & Bastani (2017) posited that in designing board games “students learn to determine the knowledge and skills needed for their games and to recognize game genres, rules and mechanisms for them to adopt and modify” (p. 46). As game designers, they need to create a context for players’ participation and anticipation of their strategies and the game emergent outcomes. Through taking such a holistic approach, learners could engage in transdisciplinary practices while addressing complex phenomena in the context of their game. This involves learners valuing diverse perspectives and making sense of relationships within and among disciplines, while intentionally engaging with the content knowledge they need in addressing the issues at hand (Kim & Bastani, 2017).

In design for supporting learners’ understanding of environmental issues, Parekh et al., (2021) used board game design to engage students in model-based inquiry and developing a systems perspective. They discussed how board game design helped learners explore the complexity of a real-world phenomenon, i.e., water pollution, and the human aspect of it, as opposed to using information to make sense of it. They argued that

Using games, like any tool, to model ecosystems requires that learners develop at least an intuitive understanding of how the natural world, man-made systems, and human activity function as interrelated systems. In addition, learners must understand games themselves as unique systems of interacting elements, that are both similar to and different from natural systems. Using games as models of other systems is a complex task, yet one that offers potentially rich opportunities for learning about the decisions involved in creating models and other representations. (p. 2150)

Their findings showed how the game design process engaged learners with identifying the elements involved in water pollution as a system and the dynamic relationships among them, and perceiving their own designed game as a system. Importantly, the study indicated that board game redesign engaged learners with a process of model building in which they iteratively revised their understanding of the problem (i.e., their game context). This demonstrated how they
could perceive their model building as a process of continuous reflections and considering various possibilities.

**Synopsis of the literature**

In this literature review, I addressed the development of complexity research and identified two significant strands of research in the learning sciences that have been influenced by complexity perspectives. The contributions of complexity discussions are, however, different in these two strands: the first strand incorporates *complexity as a frame* to study knowledge and learning conceptualized as emergent phenomena, and the second strand mostly focuses on *complexity as a subject matter*.

As shown in Table 1, the first strand offers a complexity view of knowledge. From this viewpoint, knowledge systems and knowers are not the same phenomena, each having their own nested structure. At the same time, knowledge is a living system inseparable from knowers. It evolves as knowers iteratively act upon and develop new ways of seeing and interpreting the world (Davis & Sumara, 2006; Osberg & Biesta, 2008). The mainstream of research in the second strand mostly focuses on disciplinary knowledge and on understanding the properties and mechanisms of complex natural systems. Such understanding entails a shift from linear, deterministic patterns in scientific thinking to nonlinear and probabilistic approaches (Wilensky & Resnick, 1999). In this strand, there are different examples of curricula designed based on complex systems, with an emphasis on the use of technology and individual and collaborative activities to support students’ learning.

**Table 1**

*Approaches to knowledge and knowers*

<table>
<thead>
<tr>
<th>First strand (Complexity perspectives on learning systems)</th>
<th>Second strand (Complex systems curricula)</th>
</tr>
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<tbody>
<tr>
<td>Knowledge systems (produced)</td>
<td></td>
</tr>
<tr>
<td>- Vibrant living systems</td>
<td>- ‘Organized’ systems (sciences)</td>
</tr>
<tr>
<td>- Inseparable from knowers (Davis &amp; Sumara, 2006)</td>
<td>o Focused on the structures and mechanisms of complex phenomena (Sweeney &amp; Sterman, 2007; Wilensky &amp; Resnick, 1999)</td>
</tr>
<tr>
<td>- Emergent at different levels from personal to collective</td>
<td>o Aimed at disciplinary and</td>
</tr>
</tbody>
</table>
This comparison also highlights the differences in the two lines of research in terms of the kind of relationship they promote between learners and disciplinary knowledge. In educational projects, these differences lead to different practices and designs for supporting idea generation and students’ learning (transformation). The scholarly work on the dynamics of learning and knowledge production (first strand) uses a complexity discourse to elaborate on how individual and collective learning are different but interconnected emergent systems and how knowledge is produced as learners interact with the world and expand their horizons of interpreting phenomena. This line of research, therefore, has a holistic view of knowledge, learners and the learning process. However, it has seldom elaborated on the practical implications of these theoretical views towards designing learning tools and environments. The discussions on using enabling constraints have been prominent in introducing the pragmatic potential of using complexity in educational projects. There is, however, a lack of design studies that examine the proposed design conditions within the enabling constraints debate. An important aspect of such elaboration could be about transforming mechanisms in the classroom to distribute the authorship of knowledge among learners (Davis & Sumara, 2006).

This review also points to the importance of consistency between the learning design and the subject matter and curricular goals. Appreciation of diversity and playful examination of ideas promoted in these theoretical views, would not be supported if we perceive learning topics
as set of facts to be acquired and aim to follow strict learning goals. In this vein, studies on using complex systems as subject matter promote a shift from linear, deterministic patterns in scientific thinking to nonlinear and probabilistic approaches (Wilensky & Resnick, 1999). Such an approach to learning content could specifically reinforce learners’ idea development and exchange in a complexity-informed learning setting (Bastani & Kim, 2020).

This review of the literature yields a few possible areas of future investigation. First, there has been significant theoretical development on using complexity perspectives to elaborate on the notions of knowledge and learning. The conceptual discussion on enabling constraints for structuring learning environments also signifies how complexity perspectives attend to the pragmatics of supporting learning. This approach could be enriched by using the prescribed design conditions as an analytical framework to evaluate implemented learning designs (Bielaczyc, 2006).

Second, more design studies that would explicitly use the complexity-informed conceptual framework could address its potentials in supporting learning in different contexts. Importantly, such endeavour could elaborate on the notion of enabling constraints, exploring the interim processes that support learners to bring their ideas and interests into negotiation in their collaborative efforts and engage with learning topics while pursuing their collective purposes.

Third, as discussed above, a more integrated view of design for learning to engage learners with disciplinary and interdisciplinary topics through exploring relevant complex problems could reinforce the expression and interaction of learners’ diverse perspectives. This could be conducive to implementing a complexity-informed learning setting (Bastani & Kim, 2020).

**Positioning this dissertation’s focus and learning design considerations**

This dissertation intends to contribute to the three areas discussed above; namely mapping back and re-evaluating the design elements of the already-implemented research, explicitly using complexity-informed conditions to design learning environments, and incorporating an integrated view of design for learning that would specifically attend to the learning content as an important design element.
Complexity informed design conditions

As elaborated in the literature review, the contribution of complexity views of knowledge and learning to education goes beyond analyzing and understanding learning as a complex phenomenon and includes the provision of frameworks for transforming learning systems (Davis & Sumara, 2006). The pragmatic advice of complexity perspectives takes root in the discussions on supporting multiplicity and far-from-equilibrium conditions to induce knowing and becoming and is specifically in line with the above discussed understanding of learning as complex and emergent at different levels (Doll, 1986; Sawada & Caley, 1985). Recent progress in complexity research has also contributed to moving toward the intentional prompt of the emergence of complex systems (Davis & Simmt, 2016). Incorporating these pragmatic views, however, entails realizing that emergent phenomena could not be caused, but might be stimulated through certain conditions (Davis & Simmt, 2003). This demands a shift “away from what must or should happen toward what might or could happen”. From a pragmatic view, design decisions are “more about setting boundaries and conditions for activity than about predetermining outcome” (p. 147) and aim to expand the possibilities for understanding and action. Based on the properties of emergent systems, Davis and Simmt (2003) suggested the conditions for the emergence of learning systems to include internal diversity, redundancy, decentralized control, organized randomness and neighbor interactions. These conditions are associated with both the local activities within the system and the collective behaviour of the system. In the following, I elaborate on these conditions. In chapter 3, I refer to them in the description of my design.

There have been different approaches to the fundamental problems with planning for and leading learning environments towards preset goals and certain outcomes (see Doll, 2015; Osberg & Biesta, 2008; Wien, 2015). As mentioned above, Davis and Simmt (2003) focused more on the infeasibility of causing specific outcomes in learning systems, identifying them as complex systems. From another viewpoint, Osberg and Biesta (2008) associated emergentist views with their account of educational responsibility in contemporary multicultural societies. They describe it as “a responsibility to the singularity and uniqueness of each individual student” (p. 313) and not as encouraging a particular way of being. As elaborated in the literature review, Osberg and Biesta (2007) conceptualized the curriculum as the space for new beginnings for individuals in interaction with others, and for their development as unique beings. They, therefore, emphasized creating participatory settings. Such settings challenge individuals to find
new ways of contributing to activities that are shared with others who are different from them, and to make sense of constraints of being “masters of their own actions”. This view promotes “making education difficult, for facing people with difficult and uncomfortable challenges that unsettle … [their] doings and understandings” (Osberg & Biesta, 2007, p. 37). This approach specifically contrasts defining step-by-step tasks for individuals in traditional views of education.

From a design perspective, the question would then be how learning environments could support this unsettlement, or in Sawada and Caley’s (1985) words, far-from-equilibrium states for learners. A fundamental strategy for supporting learning systems has been suggested as setting enabling constraints (Davis et al., 2015, p. 219). This points to creating the situation in which “neither ‘everyone does the same thing’, nor ‘everyone does their own thing’, but … ‘everyone participates in a joint project” (Davis & Simmt, 2003, p. 155). The notion of enabling constraints is associated with understanding complex systems as “simultaneously rule-bound (constrained) and capable of flexible, unanticipated possibilities (enabled)” (Davis et al., 2015, p. 219). Design for learning would then be about sustaining a balance between “sufficient structure” to constraint the vast possibilities and “sufficient openness” to enable diverse responses and pursuit of interests. This approach underlies the other interrelated considerations of design in this research, adapted from Davis and Sumara’s (2006) conditions for emergent learning systems. The following model (Figure 2) shows how my research adopts these interrelated conditions to inform my design. The diagram suggests how these conditions could move from a more conceptual level, at the top, toward more practical advice, at the bottom. I explain the design considerations, based on the four levels depicted in the model.
Coherence and Randomness (level 1). Enabling constraints point to structural conditions for creating a balance between coherence that supports the collective to keep its purpose and identity, and randomness that allows it to adapt and evolve. The individual elements in complex phenomena act within certain frames or rules that both make possible and constrain their actions, such as how individual players act within specific rules of games. Rules, therefore, do not prescribe particular actions but are more about determining unacceptable actions. Examples of implications of these conditions in classrooms could be providing a common ground, such as a question or activity, that is perceived as relevant and feasible by students, and trying to encourage different viewpoints, seeking alternatives, and iterative elaboration on responses. This approach is specifically different from hindering responses that deviate from the targeted content or preset goals for the classroom (Davis & Sumara, 2006).

Redundancy and Diversity (level 2). The above considerations on organizing learning systems relate to the notions of redundancy and diversity and how they both are necessary for emergent conceptual possibilities or systemic intelligence. Internal diversity defines the extent of possible responses that contribute to the system’s capacity to respond flexibly and intelligently to unexpected circumstances. A complementary quality of learning systems that sustains its existence and evolution is internal redundancy that is associated with the commonalities of agents.
**Interactivity and Expressivity (level 3).** The system’s internal diversity is closely associated with how the learning environment enables the expression of individuals’ ideas and interests. This capacity is mostly diminished in classrooms and other social groupings that are rigidly governed around the defined outcomes. It should be noted that this assertion is not about fabricating diversity, for example by formally assigning different roles to individuals in groups, but is about allowing the existing diversity in any social system to be expressed and expanded. On the other hand, the notion of redundancy is about the interactivity of the systems’ elements. In classrooms, the interactivity of individuals’ ideas could be supported by shared vocabulary, symbols and resources and more importantly by shared experiences, and purpose. This, of course, does not mean that all the members of a collective should have the same intentions and expectations: “in fact, the vibrancy of complex unities arises in the mix of its redundant and its diverse elements - or in systemic terms, the sources of its stability and its creativity” (Davis & Sumara, 2006, p. 139).

**Sharedness and Open-endedness (level 4).** Any intention to control and shape the outcomes of the collective would hinder the emergence of higher-level conceptual possibilities. As opposed to the physical structure of the classrooms, teachers cannot manage the students’ diversity of expressions and their development of ideas and interpretations. From a pragmatic view, therefore, the control of the classroom should be decentralized. This view undermines imposing authority from any individual person (or perspective) to determine what is correct, intended, and appropriate, and allows students to participate in such decisions. The design of such structures in classrooms could consider encouraging extended discussions on topics, inviting students to explain and build on one another’s interpretations, and providing multiple entry points to tasks for students’ diverse interests and emergent understandings. These could be considered under an overarching design that forms the classroom as a space for students to participate in open-ended projects. These projects could encourage students to develop shared goals and understandings while expressing and elaborating their diverse interests and novel ways of contribution (Davis et al., 2015; Davis & Sumara, 2006).

Past studies using a complex understanding of learning environments could help in developing a better sense of the affordances of different designed tools and structures for supporting students’ collective and individual actions and understanding in different contexts (e.g., Colella, 2000; Ke, 2014). Research on classroom structures that engage learners in design
practices (i.e., design-based learning) specifically showcases their potential to support students’ collaboration based on their interests and skills toward shared design goals (Ke, 2014; Kim et al., 2015; Salen, 2007). Buchanan (1992) described design as “an integrative discipline of understanding, communication and action” (p. 6) that could connect knowledge from seemingly fragmented domains, such as sciences and arts. Design practices support learners to engage in intentional interactions with their peers, teachers and learning topics, using design materials and their artifacts. Approaching learning topics through design practices could enable learners to iteratively challenge their own assumptions of problems at hand and possible solutions. Through design, learners explore new ways of knowing and doing, being involved with critical decisions (e.g., what knowledge and skills they need) that shape their learning process (Kim et al., 2015, 2019). The open-ended shared projects of design, therefore, could be a setting for students’ idea development, self-expression, and for creatively engaging with content knowledge (Ke, 2014; Kim & Bastani, 2017).

As addressed in the literature review, games have been studied by learning sciences scholars for their potential to embody disciplinary and interdisciplinary knowledge (e.g., Clark et al., 2015; Ke, 2014). Focusing on the potentials of students’ game design, Li (2010) argued that co-design of games on curricular topics could open the space for students’ imagination and “co-authoring knowledge”. Games are models of systems. Students’ participation in game design practices is about moving towards the shared goal of modeling events and situations and creating a set of possibilities for meaningful participation and interaction through the play. At the same time, students’ shared goal of “transform[ing] … ideas into communicative and coherent artifacts as playable games” engages them in the recursive and open-ended tasks of design, testing and complex problem solving (Kim & Bastani, 2017). Collaborative game design on disciplinary and cross-disciplinary topics could open the space for students to construct new relationships with knowledge systems, participate in the decision-making process (e.g., what knowledge and skills are needed for their design), and collectively construct norms of participation. Such characteristics in collaborative game design practices show potential in providing the learning design conditions proposed by complexity perspectives, importantly enabling constraints.

As discussed, this dissertation aims to contribute to the goals of mapping back and re-evaluating the design elements of an already-implemented research, explicitly using complexity-informed conditions to design learning environments and incorporating an integrated view of
design for learning that would attend to the learning content as an important design element. First, this would be followed through a complexity-informed analysis of an implemented project on elementary mathematics learning through board game redesign (Chapter 4) based on the notion of enabling constraints. Second, a math and science learning project is designed and analyzed explicitly using complexity-informed conditions (Chapter 5). An integral part of this design attends to a view of learning content that promotes nonlinear and probabilistic thinking and opens the space for juxtaposing diverse ideas in connection with complexity views of design for learning.
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Chapter 3: Research design

This chapter describes the design-based approach used in this research and the phases of this research. It also discusses this study’s particular learning design informed by complexity perspectives and developed based on a board game redesign approach in collaboration with the partner teacher. Finally, this chapter addresses the participants of the study and the methods of data collection and analysis.

A design-based approach to research

Design-based research (DBR) is a genre of research that iteratively develops theoretically-informed solutions for complex educational issues, while using this endeavour to expand the fundamental understanding that can inform future research (Barab & Squire, 2004). Reeves (2006, p. 58) referenced the work of Brown (1992) and Collins (1992) to highlight three significant aspects of DBR:

1. addressing complex problems in real contexts in collaboration with practitioners
2. integrating known and hypothetical design principles to render plausible solutions to the complex problems; and
3. conducting a reflective inquiry to test and refine innovative learning environments as well as to define new design principles.

In design-based research, the designs that aim to address the problems and affect learning communities are not developed merely by the researcher, but through the collaboration between the researcher and practitioners. My study pursues this view, being particularly informed by the scholarly work on research-practice partnership that further elaborates the aspects and requirements for this collaboration (Coburn & Penuel, 2016; O’Neill, 2016; Penuel, 2017). This approach challenges the views of bridging the gap between research and practice, as a “one-way translation of knowledge of research into practice” (Penuel et al., 2015, p. 183). It proposes addressing this gap through a continual partnership between researchers and practitioners that entails their joint work to explore problems, to study strategies, and to develop and implement designs. The studies based on this view have acknowledged the cultural and institutional boundaries between research teams and practitioners. They have, however, invited researchers to view the diversities and differences in perspectives and actions not as obstacles but as
possibilities. This diversity could be a source of learning for both researchers and practitioners through engaging in joint projects and re-establishing routines, goals, and strategies. This demands an ongoing mutual engagement that involves various phases of evaluating emerging issues and revising design strategies based on the findings of previous phases (Penuel, 2017; Penuel et al., 2015).

DBR’s iterative process and being open to emergent matters and ideas make it particularly aligned with the complexity-informed views of knowledge production, which perceive knowledge as a living system, inseparable from us, that evolves as we participate in the world and iteratively act upon and develop new ways of seeing and interpreting (Osberg & Biesta, 2008). The emphasis on addressing real problems in DBR does not limit its focus to the exploration of issues only around the initial problems and design. DBR invites researchers and practitioners to be attentive to emergent patterns in learning systems at collective and individual levels. Such “surprising occurrences” (DiSessa & Cobb, 2004, p. 86) could open new paths for exploring previously identified issues or stimulate new research orientations in future iterations (DiSessa & Cobb, 2004). Put differently, the design-based approach to research does not separate researchers’ understanding from the dynamics of emergent learning systems under study.

Understanding learning environments as complex and evolving, from the perspective of DBR, the researcher is not (and cannot be) a mere observer. They actively participate in cycles of stimulating events and developing new understandings, or in Schön’s (1983) words, in a continual “reflective conversation” (p. 95) with the situation.

Such bases also signify how DBR could be used in exploring the potentials of innovative approaches to design learning environments (Reeves, 2006). These innovative design approaches include “artifacts as well as less concrete aspects such as activity structures, institutions, scaffolds, and curricula” (The design-based research collective, 2003, pp. 5–6). Importantly, innovation through DBR embodies theoretical views of knowledge and learning that “reflect a commitment to understanding the relationships among theory, designed artifacts, and practice” (p. 6). This commitment also leads to an assertion of DBR to contribute to both practice and theoretical understandings, hence, refining and elaborating the theories that had primarily informed the research.
Phases of the design-based research in this dissertation

Complexity views of knowledge and learning discussed in Chapter 2, specifically the notion of enabling constraints (Davis & Sumara, 2006), informed the two phases of this study. The first phase involved using the framework of enabling constraints to analyze commonalities and variations in students’ design practices of a collaborative game redesign project in an elementary mathematics classroom. Based on this phase, the framework was modified using the notions of design space and self-imposed constraints from design and creativity research (Biskjaer et al., 2014; Biskjaer & Halskov, 2014; Sternberg & Kaufman, 2010) in connection with the notion of enabling constraints to focus more on the processes of the evolution of the learners’ practices and understanding. The study conducted in the second phase was the design iteration of the previous learning design examined during the first phase. The design in the second phase was focused on engaging middle school students with math and science topics through a board game redesign project where students redesigned the game Pandemic. Therefore, the complexity-framed analysis in the first phase informed the second phase, which involved using complexity perspectives in both design and analysis. The following diagram (Figure 3) shows the overall process of this design-based research. The next section elaborates more on the cycles of using complexity perspectives in this research.

Figure 3
The overall process of this design-based research
Complexity-informed analysis and design of learning

This section focuses on the learning design proposed and developed in this research. In DBR, there are reciprocal relationships among the study rationale and problem (why and what the students would learn), the conceptual framework, and the developing design (Barab & Squire, 2004). The critical review of the literature on complexity views in the learning sciences, in Chapter 2, showed the potential of complexity perspectives in conceptually framing learning designs and their studies. In the review, there were scholarly works on using complexity to analyze the affordances of learning settings (e.g., Kapur et al., 2005). However, there were not many studies on explicitly using complexity views to structure learning environments. Taking a design-based approach, this dissertation attempted to use complexity-informed design considerations in practice.

The design framework in this research adopted the notion of enabling constraints (Davis & Simmt, 2003), understanding learning systems as “simultaneously rule-bound (constrained) and capable of flexible, unanticipated possibilities (enabled)” (Davis et al., 2015, p. 219). In a nutshell, design for learning with this framework would then be about sustaining a balance between structure and openness in the following manner:

1) structure should provide guidance to constrain the vast possibilities of approaching and engaging with learning topics;
2) structure should aim to support learners’ shared goals and language; i.e., their communication;
3) openness includes encouraging (or enabling) diverse responses and pursuit of interests; and
4) openness also comes from open-ended tasks that stimulate multiple ideas and interpretations to be expressed.

First phase: A complexity-informed analysis of the Inversé project

As figure 3 shows, this design-based research includes two phases. The first phase involved a complexity-informed analysis of a project on redesigning the board game Inversé for mathematics learning. This first phase analysis explored the elements that the notion of enabling constraints highlight in the analysis and the design of learning environments. I focused on how
the collaborative game redesign approach provided the structural conditions through which the students communicated their ideas and developed shared goals and understandings. I also explored how the learners’ varied ways of using math topics unfolded in creating systems of meaningful interaction and play (i.e., board games). This analysis indicated the importance of structured constraints at the starting point, which include the students’ playing the same game and having the shared goal of redesigning, in supporting common language and idea exchange at the class and group levels. It also highlighted how the groups’ progress and the unique paths of developing their designs and use of learning topics were essentially intertwined with the groups’ co-constructed constraints. These emergent constraints included their goals and decisions on incorporating specific game features, how to split or share tasks, and how complex or challenging their game should be. Put differently, this phase was about “reverse engineering” an already implemented learning design, i.e., “mapping back” its elements (Bielaczyc, 2006, p. 317), through the lens of the enabling constraints framework. This helped me make design decisions implemented in the Inversé redesign project more explicit, classifying them according to the design elements recommended by complexity perspectives (Bielaczyc, 2006). It highlighted the design elements in this board game redesign approach that could contribute to students' idea development and expanding their use of mathematics. At the same time, this analysis explored what was structured and what unfolded in this game redesign project (i.e., commonalities, diverse ideas, and groups’ variations in using mathematics). It, therefore, showcased the need for a deeper exploration of the enabling constraints notion in connection with students’ practices and processes and the kinds of interactions that could happen using a board-game redesign approach. In other words, I felt the need to delve into how this approach could open the space for different ideas and interpretations to be expressed and the groups’ use of learning topics to evolve.

In the first phase (Inversé project), therefore, the complexity framework was used for analyzing data. The study conducted in the second phase (Pandemic Project), elaborated in the next section, was a design iteration of the Inversé project using the board game redesign approach and complexity perspectives for both the design and the analysis of the study.
Second phase: A complexity-informed learning design and analysis

The Pandemic redesign project (second phase) adopted the approach from the first phase project on math game redesign. I considered the potentials of board game redesign practices based on our analysis on the Inversé project, and the current study’s learning goals for students (e.g., using grade-7 math and science topics in exploring and designing emergent systems) and the specific school and classroom context. In this phase, I used the notions of design space and self-imposed constraints from design and creativity research (Biskjaer et al., 2014; Biskjaer & Halskov, 2014; Sternberg & Kaufman, 2010) in line with the notion of enabling constraints. This was to focus more on the processes of the evolution of the learners’ practices and understanding and explore what the underlying elements that stimulate the emergent learning opportunities for learners are. In the following, I elaborate on the subsequent steps that shaped the design of the learning activities.

Choosing the board game structure

The learning goals for students included engaging with complex systems and using learning topics in math and science (e.g., statistics and probability and interactions and ecosystems). In considering different thematic board games to address these goals, cooperation (as opposed to competition in board games) surfaced as one of the criteria. In cooperative games (or “collaborative games” according to Zagal et al.’s (2006) categorization), players work together towards common goals and win or lose together as a team. They, then, need to coordinate how to use their powers and resources and their actions through the game (Berland & Lee, 2011). There are two main reasons that a cooperative board game was considered to be more appropriate in this game redesign project: (1) the interaction and collaboration space shaped through cooperative play; and (2) the complex structure of cooperative games and their emergent outcomes.

The interaction space shaping through play. In cooperative games, players help one another to better understand the game system and move forward in the game. They express their ideas and motivations for their actions to collectively strategize and win the game. As Berland and Lee (2011) put it, in cooperative games “players must externalize their thinking processes and collaborate on their actions. Because coordination is necessary to win the game, it makes the development of rule understanding and group strategy formation an important part of the
thinking and reasoning that takes place” (p. 79). This is in contrast with competitive games in which players may hide their motivations and strategies in order to get advantage and possibly win the game. In a game redesign project, students need to make sense of the original game’s rules and explore various play and strategizing possibilities. The collaboration space in playing cooperative board games would significantly support learners’ shared understanding of the game system.

**Potentials of redesigning cooperative games.** Games could represent complex structures (Gee, 2008). Well-designed cooperative games need to allow for multiple play trajectories in order to make them replayable. They would assign different roles to players so that the decision making power could be distributed among them while they cooperate as a team. In addition, they would provide obstacles and complicated problems that reinforce players’ working together. The possibility of following different strategies in different rounds of game play also needs the game structure to both embody chance and allow for strategizing (Seif El-Nasr et al., 2010; Zagal et al., 2006). This also promotes a need for using different elements (e.g., resources, ways of moving across the board, random events, trade of resources, etc.) in the game for players’ different actions and decisions. These characteristics of well-designed cooperative games could make them models of complex structures that allow for emergent outcomes.

To redesign any type of game, learners would need to play the original game and make sense of its structure. Redesigning a cooperative board game could therefore provide the opportunity for learners to engage with a complex system and the possibilities its various elements could provide. As discussed above, learners’ understanding of the game system could be facilitated by openly discussing their ideas and actions and developing group strategies.

Besides, redesigning a cooperative board game could engage students in creating another cooperative system, where the interaction of different elements and players’ skills would help them collectively overcome a complex problem. This approach would be specifically relevant to contemporary issues of our world that increasingly require joint efforts rather than maximizing one’s benefits.

**Developing the board game redesign project**

This project was conducted in Fall 2018 and early 2019 at McCarthy (pseudonym) middle school in Alberta. The school’s approach is to deliver the subject matters not in isolation,
but as connected and as the content of the problems that students can engage with through creative projects. The school has a focus on innovative research-informed practices (McCarthy School’s mission documents, 2019). Design thinking and learning through design is specifically considered as one of the pillars of this school (Annual education results report, 2017-2020; McCarthy School’s mission documents, 2019). They have been incorporated and promoted by the school through the past years, engaging in different action research and collaboration with design and education scholars and conducting professional development programs for educators. The school sees the value of design-based practices in creating the setting for students’ engaging with complex interdisciplinary problems (Design Thinking in McCarthy School’s mission documents, 2019). Beyond that, they emphasize,

Design thinking inspires the confidence that everyone can be part of creating a more desirable future. Design thinking is a process that enables us to take action when faced with difficult challenges. The challenges students are confronted with are real, complex, and varied. They require new perspectives, new tools, and new approaches. Design thinking is one of them. (p. 2)

The students at this middle school, therefore, had experience with various collaborative creative design projects. I conducted this study in collaboration with the grade-7 mathematics teacher, Marc (pseudonym). He pursued an approach of using innovative practices and interdisciplinary projects and had extensive experience with both digital and board games, being a game designer himself. He had also collaborated in different research projects and scholarly work in the past.

Meeting in early Fall 2018, the teacher and I discussed the use of a board game redesign approach in his class. This design project was in line with the school’s and the teacher’s view of engaging students with curricular topics through creative experiences. The school’s particular focus for that academic year was on mathematics and specifically numeracy. As the grade-7 math teacher, Marc was exploring the possibilities of engaging students with grade-7 math topics, including numeracy. Based on the school’s and his own view of teaching and learning, his approach was using creative projects that support interdisciplinary learning, not treating mathematics as an isolated subject matter, for his class.
**Pandemic redesign project.** Exploring different thematic cooperative board games, the *Pandemic* board game (Z-M.A.N. games, 2007) was considered as a possibility, considering the learning goals, the teacher’s and the school’s approach and the classroom context.

This board game models disease spread across the world. Players take different roles and work together to treat infected populations and prevent outbreaks to buy enough time to complete the ultimate objective which is the discovery of the cures. This cooperative game demonstrates the interdependencies of different components in a global issue (i.e., pandemic) and how small or random changes could create unexpected patterns (e.g., through a new region suddenly getting infected and causing an outbreak). It was expected that the game would also be interesting to the students. This project was conducted in 2018 and 2019 before the COVID-19 pandemic broke out and as such the game theme was considered hypothetical at the time. I particularly found this game a good fit to grade-7 math topics of numbers, statistics and probability as the game’s system of play relied upon such elements (e.g., infection rates, probability-based outbreaks, etc.). The game’s theme was a complex issue that could be explored from a scientific approach and promote student collaboration. It was specifically connected to the grade-7 science topics of interactions and ecosystems. The different roles in this game could also model the different aspects of such issues and the human impact on intensifying or controlling them. It was expected that the math topics of focus could give a structure to students’ exploring the original game system and to their game redesign endeavour, and their use of science topics emerge as they decide about their game theme and develop the game backstory. In redesigning the *Pandemic* game, students could decide to change the main problem of the game (disease spread), for example, considering an ecosystem-related issue or a sci-fi theme.

The teacher and I evaluated the potential of using the cooperative game *Pandemic* for engaging students with mathematics topics in his class. Marc was familiar with this board game and saw significant learning opportunities in this game redesign project. He was also interested in working with the science teacher to make it an interdisciplinary project. At the time, Marc was designing a board game and considered his own experience valuable in conducting this project with the students. Discussing the integration of the curricular goals in this creative project of board game redesign, he also explained his stance on the redesign process, in my interview with him:
Just to talk about the idea of creation and destruction in art, I truly believe that art is even if you’re destroying something which a redesign is, you’re destroying something in front of you that is a form of creation because you have something in mind after you’re done. So, even if you’re like tearing something apart... if you’re blowing something up that’s still a part of the creative process because yeah you have something else in mind. ... That’s what all art is, that’s what all redesign is and that’s where the learning is.

**Implementation scheme.** After getting the school’s principal’s confirmation for the project, Marc and I discussed the project’s process and goals in more detail. For the start of the project, he was willing to also discuss with the students the possibility of incorporating an explicit art form, based on their groups’ interests, and exploring the connections to math and science. This was discussed as a possibility with the students in the first session. We also discussed using *Pandemic Iberia*, another version or an existing redesign of *Pandemic*, with a more geographic and historical focus in its theme. As Marc mentioned, “[t]he illustrations booklet for Iberia is amazing with geometric Moorish-inspired designs as well as figurative drawing. It is also interesting because it is a historical 1800’s era and could show us the way to include history and geography in our already interdisciplinary math/science approach”. We discussed the potential of using both versions. After the start of the project, Marc asked one group, with their subsequent agreement, to redesign *Pandemic Iberia.*

Students worked on this project in small groups of 4-5 members. For determining the groups, the teacher asked each student to write the name of one person they prefer to work with and one person they do not. Based on this, he grouped the students in a way that they would work both with others who had a good teamwork experience with and the students who they had not worked with. His goal was for students to try to participate in joint projects that would include diverse viewpoints. The following table (first and second column) shows the overall stages (structure) that the groups went through in this game redesign project. The third column indicates the design conjectures, informed by complexity perspectives, supporting each stage.
### Table 2

Pandemic redesign project stages and associated design conjectures

<table>
<thead>
<tr>
<th>Project stage</th>
<th>Description</th>
<th>Supporting learning design conjectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Playing <em>Pandemic</em> in groups and mastering the rules</td>
<td>Initial sessions were allocated to the groups’ playing the original game together.</td>
<td>Students’ shared understanding of the original game rules and goals would help them exchange design ideas (shared vocabulary, symbols and resources)</td>
</tr>
<tr>
<td>Brainstorming on possible changes and their game theme</td>
<td>In the play sessions, students discussed the game stories of their interest and how to use learning topics</td>
<td>Group brainstorming would open the space for diverse interests and ideas to be expressed and interact. (Enabling groups’ internal diversity)</td>
</tr>
<tr>
<td>Narrowing down ideas on using math and science topics with the teacher</td>
<td>The teacher sat with each group to discuss their ideas and help them reach initial consensus</td>
<td>Groups’ focus and collective purpose would support the interactivity of the individuals’ ideas. (Acting within certain frames both constrain and make possible their actions)</td>
</tr>
<tr>
<td>Designing and playtesting their games</td>
<td>The groups started their designs and aimed to test their game drafts</td>
<td>Iterative design practices would involve evolving goal setting and decision making. This could enable learners’ diverse ways of contribution and their revising assumptions. This process could support learners to practice their agency in identifying and addressing the problems and expanding the use of learning topics.</td>
</tr>
<tr>
<td>Inviting their classmates and other classes to play their games</td>
<td>Their classmates and other grades played their games</td>
<td>The anticipation of sharing their designs with others outside their group would encourage them to seek multiple viewpoints and design possibilities. It could also act as a motivation to have a playable and balanced game.</td>
</tr>
</tbody>
</table>
Reflecting on the project
possible future changes

The class reflected on the project. They also reflected on what they would change in their own games in their groups and individually.

As learners confront their own designs with their applications in the world, they could develop a more holistic view and see more complex interconnections among problems at hand. Reflecting on their experience would help them explore more possibilities of evolving their design in a meaningful way.

Participants, data collection and analysis

Participants

The participants of this research were the grade-7 teacher and students in a middle school in Calgary. I collaborated with the teacher in designing the learning activities for students with a focus on supporting their understanding of topics in mathematics and science curricula.

The study took between 45 minutes to 1.5 hours of class time two or three school days per week, for a total of 18 sessions, from October to December 2018. The follow up interviews with students and the teacher took place in January 2019.

To select the school and the classrooms, I looked for the teachers that had experience with design-based learning and were willing to engage in new approaches to the development of participatory learning environments. It was critical that the teacher would be willing to participate in the design, execution, and reflection throughout the study. Potential teacher participants were identified through recommendations from my supervisor’s Calgary Board of Education (CBE) network and her own contacts with schools based on her past research projects in Calgary. Going through this process, I started this joint project with a grade-7 mathematics teacher in an art immersion middle school in Calgary.

As mentioned above, in this classroom, students who were willing to participate were included. The theoretical frame (the complexity approach) that informs this study evaluates the diversity inherent in learners’ groups in terms of their ideas, interests and understandings of curricular topics as necessary for supporting their collective and individual learning. This study, therefore, did not exclude any student present in the classroom from participating and aimed to encourage students to express their voice and find their own ways of contribution in group activities through the designed learning environment.
All the 23 students from this class, constituting five groups, were invited to participate. From them, 18 students consented to participate in this research. The teacher was also informed that all the students, including those who chose not to participate in the research, would participate in the activities, however, data would not be collected from non-participants during their activities. This information was also provided in the student assent and parent consent form. Only myself and my supervisor were informed about which students had chosen to participate.

This study was conducted as students were engaged with in-class group activities designed in collaboration with the teacher. Non-participants, therefore, continued their group work, but the cameras were adjusted in a way that they did not capture non-participants. Given the participatory nature of design-based research, which takes place in the rich, complex context of a classroom, there could be times when data is captured from non-participants (e.g., if a participant is being videotaped and a non-participant enters the scene and talks to them). While I did my best to ensure that the data was collected only from participants, I ensured that it was not shared or used for analysis if any of the non-participants’ videos or voices were unintentionally captured.

The consent form also asked for the individuals’ permission on the researcher’s use of their group artifacts (this option was for both the individuals who were willing to participate in the study and those who decided not to). If the permission was granted, the artifacts were used in a way that the non-participants’ individual work could not be identified.

**Data collection**

This study used multiple sources and methods of data collection that have been considered essential for cross-checking and taking multiple perspectives on complex events and issues (Pelto & Pelto, 1978). Data collection in this research drew upon ethnographic approaches and adapted the major strategies that have been used within these approaches. These strategies included participant-observation, interviewing, and external sources (Wolcott, 1999). In the following, I address how these strategies were adopted in this study, using different tools and techniques suggested by qualitative researchers (e.g., Merriam, 2009; Simons, 2009).

*Participant-observation* is an integral part of the fieldwork. Ethnographic observation requires “looking for those mutually understood sets of expectations and explanations that enable us to interpret what is occurring and what meanings are probably being attributed by others
present” (Wolcott, 1999, p. 159). In this study, I observed students’ activities, discussions and design processes, being present in the classroom. My observations were accompanied by notetaking, photography and video-recording that could capture many verbal and non-verbal cues to understand the context and students’ interactions with their peers and teachers. Following Wolcott’s recommendation, I attempted to do the write-up as much as possible through observation as it helped me identify the possible issues that could be explored through further data collection to enrich my inquiry.

Introducing interviewing as the second major data collection strategy, Wolcott posits that the interviewer role is a critical role for researchers as they actively “ask”. Another form is interviewing participants about their historical stories to make sense of how things were in the social settings under study before the researcher’s involvement with them, and how they perceived change in the setting. Informal interviewing could also be used besides formal interviewing. It includes a range of interactions, from casual conversation to direct questioning, and could be even more important than a formal interview.

This study used the interviewing strategy, in both the informal and formal forms, at different stages of the research. This was a critical way to make sense of groups’ collective ideas and designs and understand individual students’ interpretations and contributions.

The informal interviews included conversations between the researcher, i.e., myself, and students while they were working on their projects in the class. These included questions by the researcher about the students’ specific decisions, their artifacts, and their planning for next steps. In conducting formal interviews with groups and individual students, I used open-ended questions. This provided the possibility of asking interpretive questions to clarify tentative answers and to move toward a shared understanding with the participants (Merriam, 2009; Simons, 2009). To remind the students of the design process and prompt discussions about the project, I also used the photographs that I had taken of the students’ group work and designed artifacts. I also interviewed the teacher about his experience with the project and how he adapted his strategies based on emergent issues.

The third strategy to collect data was using external resources for further exploration of the classroom processes and history and its broader environment (Wolcott, 1999). These
resources included the school’s documents about their overall vision and approach to learning, importantly their views towards interdisciplinarity and design-based learning.

**Analysis**

My analysis focused on the dynamics of students’ collective understanding and action represented in group discussions and the use and creation of artifacts. It also included how individual students’ interpretations prompted new paths for collective problem solving and exploring learning topics (Cobb, 1999). Informed by complexity perspectives, the analysis attempted to make sense of the common grounds that supported the interaction of ideas. It also explored the variations that emerged in groups’ design trajectories and artifacts, considering how the juxtaposition and blend of diverse responses triggered qualitatively different collective insights that transcend individual ideas (Davis & Simmt, 2003). Providing descriptions of segments of data supported identifying the critical events that prompted new possibilities for individual and collective idea development and action (Towers et al., 2013). This method was implemented through chunking observation notes and video data into episodes that presented a shift in students’ focus and changes in their practices (Barab et al., 2001; Kim & Ho, 2018). I specifically explored how learners’ decisions triggered new paths of problem solving and use of learning topics, transforming their designs. The details of data analysis methods in the first and second phase of the study are discussed in the next two chapters. The following table provides an overall view of the frame and focus of analysis in these two phases.

**Table 3**

*Frame and focus of analysis in the two phases of this study*

<table>
<thead>
<tr>
<th>Phase</th>
<th>Informing Frame</th>
<th>Analysis focus</th>
</tr>
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<tbody>
<tr>
<td>Phase 1</td>
<td>Enabling constraints (Davis &amp; Simmt, 2003)</td>
<td>- Class and group level co-constructed commonalities</td>
</tr>
<tr>
<td>(Inversé Redesign project)</td>
<td></td>
<td>- Students’ expression of their diverse design ideas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Evolution and convergence of learners’ ideas on using mathematical constructs to create play situations and unique games</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Enabling constraints in connection with the notions of self-imposed constraints and evolving design space (Biskjaer &amp; Halskov, 2014)</td>
<td>- Critical episodes of transforming collective design spaces emerging through the interaction of learners’ ideas, design materials and activities</td>
</tr>
<tr>
<td>(Pandemic redesign project)</td>
<td></td>
<td>- How learners’ decisions enabled them to expand their ideas and possibilities of using math and science topics</td>
</tr>
</tbody>
</table>
Further remarks on ethical considerations

The section describing the research participants, addressed some ethical considerations of this study. The purposes of understanding and affecting classrooms’ processes and stimulating new relations and interactions among participants, require me as the researcher to follow important ethical research guidelines. Beyond the required formal processes, I needed to be attentive to delicate and emergent matters in protecting participants’ privacy, constructing relationships with them, and understanding their perspectives (Josselson, 2013). This specifically involves considering the dynamics of authority between me, as the researcher, and participants, and among the participants, and identifying vulnerabilities. Most participants in the two phases of my study include school level children who are a particularly vulnerable group. In the second phase, where I was directly responsible for conducting the project and collecting data, I followed strict protocols with regards to how the project was explained to the students trying to make sure it does not adversely affect class routines and learners’ engagement, how their parents’ consent and their own assent was obtained, and importantly how their confidentiality and data privacy was ensured. Of note, all interactions with students were done in the safe environment of their school with direct consultation at every step with their teachers.

Ethical concerns could also be reflected in the interpretation and dissemination of findings. Key considerations, among others, were attempting to arrive at shared understanding with participants in the cycles of study and making sense of the events and expressions in context and taking care of matters of anonymity.
References


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Chapter 4: Phase one, the *Inversé* redesign project

This chapter discusses the first phase of my doctoral study, i.e., a complexity-informed analysis of a project on board game redesign for mathematics learning. This project was conducted with grade-3/4 students in a Western Canadian public school. Using the framework of enabling constraints (Davis & Sumara, 2006), this analysis explores the commonalities and variations in students’ practices of redesigning the board game *Inversé* for mathematics learning.

From complexity perspectives, learning emerges through the interactions of alternative interpretations. Scholars encourage educators to create conditions open to the emergence of different forms of learning in the classroom (Davis & Sumara, 2006). To support learners’ communication, the structure should engage them in common experiences, such as shared projects and use of common tools and materials. Such settings should, at the same time, involve tasks that invite different ways of contribution, encouraging learners to express their diverse idiosyncratic ideas. Using this complexity-informed framing, I explore how students engaged with mathematical thinking in communicating their ideas, collaborated to create rules of interaction for a working system (i.e., a game), and provided unique possibilities of play for themselves and others. The following questions guide the analysis: (1) how the collaborative game redesign approach used in this project provided the structural conditions through which students communicated their ideas and developed shared goals and understandings; and (2) how the groups’ varied ways of using mathematical constructs in creating systems of meaningful interaction and play unfolded through the project.

Based on the results of a previous project on students’ board game design for learning, which showed students’ difficulty in designing board games from the scratch (Kim & Bastani, 2017), this project was designed for grade-3/4 mathematics learning through redesigning an existing board game. It was conducted in two to three forty-five-minute sessions per week, over six weeks. Ethnographic data was collected through field notes, video-recordings of the classroom and photos of students’ in-progress and final game designs.

Mathematical competency has been widely supported through routine practices of solving linear and defined problems in schools (i.e., established mathematical models of a situation, such as how to evenly spread soil in an area) (Zawojewski et al., 2003). Therefore, the focus has been on computation rather than using mathematics as a modeling tool (Davis, 2018). Shifting the
focus to the latter could open the space for learners to playfully experiment with their own assumptions and the mathematical constructs to make sense of real-world phenomena. Viewing mathematics as a means for interpreting and modeling systems (Davis, 2018; Lesh & English, 2005), mathematics learning would not be merely about practicing computation and solving already mathematized problems that use linearizing assumptions (e.g., limiting the range of inputs). It would be about how learners use mathematical constructs as a tool to model patterns and future possibilities in making sense of the phenomena that shape their lives (e.g., population growth).

Using a game redesign approach this project aimed to provide the opportunities to use mathematics to create rules and patterns. It was expected that the board game redesign project engages learners in making sense of the rules of the original game, *Inversé*, which involved working with multiple cuboids that needed to be strategically placed on a grid board, and using mathematical concepts (mainly area and estimation) to create new game systems. Learners could engage with how using various game components (e.g., dice and grid board) in relation to one another could create various play situation and game dynamics, and how mathematics could be used in communicating their ideas and implementing their design choices.

It was conjectured that the game redesign approach could enable learners to express their individual ideas while having more possibilities for their ideas to interact with those of others toward collective learning.

**Board game design for mathematics learning**

Games are rule-based structures aiming to engage players in navigating a modeled world. Signifying the systemic nature of games, scholars in different fields such as management, economics, engineering and education have argued for using games in understanding complex phenomena and supporting a systems view of events (e.g., Gee, 2008; Kafai, 2006; Meadows et al., 2016; Mkondiwa, 2020; Sengupta & Clark, 2016). This entails making sense of the rules and structures that underlie the dynamics of those phenomena, and the unexpected behaviors that could arise from such structures. “Any game is a kind of miniature artificial system” enacted by its rules (Zimmerman, 2013, p. 158). Games as models of systems, bounded by a set of integrated rules that underlie its dynamic surface, can be approached from a mathematical view. This includes the logic behind the structure, which makes the play meaningful, and the involved
mathematical concepts including probability and statistics, optimization, and sets (Benthem, 2014; Dresher, 2012). Designing games could specifically make mathematical thinking explicit, for example, in deciding about the rules of players’ interactions and game economy, and making the game replayable (e.g., through using chance). As a special case, non-trivia math games (e.g., Qwirkle, Ticket to Ride, Inversé, Kingdomino, Escape From the Aliens) could manifest the application of math in the play and design process, including spatial thinking using two- and three-dimensional shapes and understanding and creating graphs and sets through visual elements.

The approach of the study addressed in this chapter speaks to viewing mathematics as a tool for interpreting and modeling systems, phenomena and experiences (Davis, 2018; R. Lesh & English, 2005; Zawojewski et al., 2003). In addition, this project viewed mathematics as a means to mediate learners’ imagination and design of new possibilities. When viewing mathematics as the study of structure, and as a tool for making sense of complex systems that shape our everyday lives (e.g., economic systems and communication networks), supporting mathematics learning should go beyond providing the linear path of reaching goals from givens and practicing computation (R. Lesh & English, 2005). Engaging with non-trivial problems requires “a series of modeling cycles in which current ways of thinking are iteratively expressed, tested, and revised; and, each modeling cycle tends to involve somewhat different interpretations of givens, goals, and possible solution steps” (p. 489). When making modeling the focus of school mathematics, mathematical constructs will be used in the service of interpreting situations and phenomena, i.e., within the modeling activity. In a modeling activity, computation is not the center of learners’ mathematics practices, but “a means to an end” (Davis, 2018, p. 84).

Studies have highlighted the potential of board game play and design in developing mathematical competencies (Kim, Bastani & Takeuchi, 2021; Nasir, 2005; Saxe, 1992). As discussed above, games are rule-based structures, in which players act on the representations of a modeled world. While in a digital game the rules are enforced by the computer, a board game relies completely on players to collectively understand the rules and execute them (Berland & Lee, 2011). Following a view of mathematics as a tool for interpreting and modeling systems, this project not only used game play, but also proposed collaborative redesign of board games as the activity that could support learners’ mathematical thinking. It was expected that redesigning board games would provide unique opportunities for learners to explore the structure of pre-
existing games, and beyond that, to imagine and experiment with new possible structures to create meaningful situations for play. Such experimentation would be mediated by the different tools and materials (e.g., games’ symbolic pieces, board, and dice) that students use in creating players’ resources and rules of their interaction and progress in the modeled world of the game. Through creating game components, learners engage in iterative problem solving that involves numbers and spatial sense (Barta & Schaelling, 1998; Saxe, 1992), e.g., using measurements, shapes and transformations in creating game pieces, board and scoring system, and probability problems in addressing chance and uncertainty. In designing games for mathematics learning, students’ use of mathematical constructs and calculation for precise measurements would be a means to entertain and communicate various imagined possibilities, not an end in itself (Davis, 2018; Nemirovsky & Ferrara, 2009).

**Project context and data analysis**

The collaborative game design approach used in this project involved using multiple modes and materials for communicating and negotiating ideas and transforming them into shareable artifacts (Kim & Bastani, 2018). By choosing signs, symbols, and rules, learners could create coherent systems (i.e., games) that set multiple situations for players’ participation in motion. In this study, all the groups started with the shared goal of creating a 2-dimensional (2D) version of the game *Inversé* and went through cycles of playtesting to balance their game. Students’ designs, however, unfolded in various ways, differentiating the final games in terms of components, rules, number of players and the degree to which they relied on players’ chance or strategy. Below, I discuss the project structure, which provided common grounds for students’ communication within and among the groups, to describe the classroom context. I also discuss the commonalities at the group and class levels that were co-constructed through iterative practices, and how they extended students’ shared understandings and exploration of possible designs (Kim, 2018). I then describe the findings on students’ emergent co-designs. This includes how their ideas were expressed, evolved and converged into shareable artifacts, and the ways they used mathematical constructs to create play situations in their unique games. I specifically provide examples from the interactions and designed artifacts of two groups in this classroom, which I refer to by the name of their designed games, *Extreme Versé* and *Markit*. The teacher’s and students’ names used here are pseudonyms.
The groups consisted of grade-3 and -4 students with diverse backgrounds. The group Extreme Versé had three members. Sajan and Talia were grade-4 students and Avani was in grade 3. Talia was from Canada and Sajan and Avani were from India and had immigrated with their families to Canada. Avani was absent a few sessions in the project but was engaged with the design and making of the game components when she was present.

The group Markit also had three members. Elena, a grade-4 student, was from Serbia. Aaron was from Eritrea and was a grade-3 student. Natalie was also a grade-3 student and was from Ukraine. Throughout the project, Elena and Aaron were more engaged with the design process. Natalie was not always present during these sessions but participated in making their game components and the playtesting of their game with other group members, towards the end of the project.

Commonalities as infrastructure for communication and idea development

The project shared goals. The project’s structure included the main goals of creating a 2-dimensional version of the Inversé board game and the use of multiplication and estimation in the redesigned games. The teacher, Ms. Lennox, discussed these goals with students in the initial sessions. These shared purposes became the bases for students’ idea exchange, interactions with other groups and making sense of their redesigned games, and ongoing discussions with their teacher throughout the project.

Creating a 2D version of Inversé. Before starting the project, students played multiple games and with their teacher, Ms. Gagne, chose Inversé as the game to be redesigned. Inversé, as a two-player game, has a set of five different wooden blocks with the same volume but different dimensions for each player. Players take turns to place their pieces until one of them can no longer fit a piece. Its rules include not touching same-color pieces, not placing same-color pieces in the same orientation, and not touching same-height pieces (Figure 4). In each turn, the player should consider possible positions of their 3D pieces to fit them on the board while making the next move more difficult for the opponent. It, therefore, could engage learners with the concepts of volume and area (as they try the different faces of blocks on the game grid board), rotation and estimation. In redesigning Inversé, learners were expected to explore the game structure and transform the components and rules to create a game with 2D pieces. Initially, the teacher asked students to think about possible designs individually, and then had them share their ideas in
groups and integrate them into one game. She emphasized listening to others’ viewpoints and being ready to change the design ideas in this process. The common starting point, i.e., playing Inversé and understanding its rules, having the shared goal of changing this game into a 2D game, and using simple materials (grid papers, scissors and markers) facilitated the communication within the groups. It also helped them easily make sense of other groups’ designs when shared.

**Figure 4**

*Inversé: (a) the game pieces (b) a possible play situation based on the rules*

![Figure 4](image)

*Using multiplication and estimation.* In the subsequent sessions, Ms. Gagne discussed developing math skills in multiplication and estimation as one of the goals of students’ games. She asked students to decide about their game components (e.g., players’ pieces, dice, and board) and their size, and how they want to use them in their game.

The game *Extreme Versé* (Sajan, Avani, and Talia) started with cutting and coloring different rectangular pieces (Figure 5, green pieces) and making cards that showed two numbers (Figure 5, white paper pieces with numbers). Sajan explained to Ms. Gagne (Figure 5) that the numbers on each card showed the perimeter of a rectangle (although there were two numbers on each card) and that players should estimate the rectangle’s area based on the perimeter and choose the right one among the pieces. Each turn, players would randomly pick one card and choose the right piece and put it on a grid paper used as the game board. The player who could fit all their pieces on the board would win. Ms. Gagne complimented them for having a good starting point for discussing the concepts of perimeter and area. However, it seemed that there existed a confusion about these concepts in the group. Using Inversé’s original grid-like game board, she showed an example of a block covering a 3×2 area (the red block). She then drew a 3×2 rectangle on a grid paper and wanted the students to explain how they could find its
perimeter and area. It was primarily to challenge them to distinguish between these two concepts. Sajan gave correct answers and the teacher wanted all the group members to work more on the same example. She also asked them to explain again what the two numbers on their cards mean. Avani mentioned the numbers specified the width and length of the rectangle that players should pick. This was different from Sajan’s initial explanation. Ms. Gagne suggested that they could also create a card for each piece specifying its area and perimeter. Ms. Gagne visited different groups and went through a similar process of discussing area estimation for creating their game pieces.

**Figure 5**
The group discussing the concepts of perimeter and area with the teacher

![Image](image)

**Co-constructed commonalities.** We observed that the initial intentional conditions that the project started with (i.e., playing a specific game and redesigning it with a focus on using the constructs of multiplication and estimation) stimulated certain kinds of discussions and iterative practices. This supported the interactivity at the group and class levels and extended the learning possibilities for students. The following also discusses how learners’ shared vocabulary and understanding of the process developed throughout the project. These unfolding commonalities further supported idea exchange on possible designs in making a coherent playable game and the unique design trajectories taken by groups that reflected their choices and interests. Using examples of the design practices of the groups of focus, this section mainly explores two emergent themes: the shared expectation of designing balanced games and the shared understanding of the design process as iterative and collaborative.

**The shared expectation of creating a balance between chance and strategy.** As students implemented different design ideas, we observed that they started having deeper discussions on their designed rules, signs, symbols (e.g., numbers) and their game components. The *Extreme*
Versé group discussed using the number cards they had initially designed (players would randomly pick one card to choose the right rectangular piece and play with):

Sajan: Now I kind of feel removing the cards, because it more tells you what to do. It doesn’t show you your thing.
Talia: (But) we need some randomness.
Sajan: We do not need randomness. How about without randomness?
Avani: Why did you make these cards? ... Without the cards it would not be a math game. It would be take a piece and place it, take a piece and place it.

Such conversations around how to make their games based on player decisions versus chance as well as what it means to use math in designing their games (as observed in Avani’s comment above) also emerged among other groups and continued throughout the project. Ms. Gagne, who frequently plays board games outside the school context, also focused on how games should provide situations for meaningful decision making and strategizing, rather than testing calculation skills or just how lucky a player is.

Another group, Markit, came up with the idea of using two dice for players to draw rectangles on a grid board and to use multiplication. The numbers on the dice determined the rectangles’ widths and lengths. Players had to find a free space on the grid board to draw their rectangle. In a discussion with the group, Ms. Gagne acknowledged that their idea of using dice rather than prepared rectangular pieces would push players to think of the area as they drew rectangles. She, however, challenged the group to think about how they could change their game components “to make their game more complex,” requiring players’ meaningful decisions. This conversation stimulated a discussion on how changing the board size or even using dice with bigger numbers (Figure 6) and adding rules would create more challenging play situations. A common language, involving “strategy vs. chance”, “not creating knowledge testing games” (for calculation skills), “estimation”, “decision making” and “randomness” emerged out of the class- and group-level conversations. The shared expectation of the games being more based on strategy as opposed to chance supported learners’ communication and idea development in their group playtests as well as when they provided feedback on other games. Importantly, it opened the space for students to further explore how using different components and mathematical constructs (e.g., area) could lead to different play situations, which I evaluate further.
Understanding game design as an iterative and collaborative process. As described above, from the beginning, students were encouraged to try different design ideas and change them as they tested their games. Playtesting, then, was a significant part of students’ work and essentially engaged all the group members. Creating a playable game is about anticipating different situations and opening the space for even unexpected strategies, which differentiate game design from other kinds of design projects (Kim & Bastani, 2017). Other groups, as well as the students from another class, also playtested the games and gave feedback on. This helped the groups have new design ideas to improve upon their games (Figure 7). We observed how playtesting and encountering unexpected outcomes gradually shaped a shared understanding of game design as a dynamic and collaborative process.

In our interview with the Markit group (Elena, Aaron, and Natalie), Elena described game design as challenging while also emergent and fun: “because you have a game but then you
have to make a different version of it, so then it’s also kind of fun because one day you might just become famous for making a new version of a game.”

**Emergent game design variations: Evolving design ideas and mathematics practices**

The commonalities in the classroom, which acted as structured or emergent frames, supported the groups and the class to maintain their collective purpose and coherence, and facilitated the communication of students’ individual ideas. In addition, we view these commonalities for supporting students’ interactions necessary for the emergence of design variations in the open-ended task of creating games. This section further explores how the process of game design and playtesting opened the space for students to reimagine possible interaction situations and, consequently, for variations in their artifacts and use of mathematics to emerge. Although all the games used a grid board and rectangles, the final games were all unique, in terms of the number of players, how players picked rectangles (using dice or prepared pieces), the rules for placing or drawing rectangles (e.g., if and how the rectangles could touch), and the rules for winning (e.g., by trapping the opponent’s rectangles or by fitting the last piece). To evaluate the ways students used mathematics in designing their games, I focus on two main categories that all the games could fall into: having prepared rectangular pieces or using dice for drawing pieces. We specifically found *Extreme Versé* and *Markit* as good examples of the designed games in these two different categories. Using these examples, I discuss individual design ideas contributing to emergent collective design decisions in the groups in the process of learners’ collaborative game design.

**Diverse individual ideas about game features.** In the process of group game design, we observed how diverse ideas of individual students based on their interests in particular game features triggered a sequence of design decisions and use of math in each group.

**Extreme Versé: Designing a three-player game using prepared pieces.** After revising their game’s first version, described above, Sajan suggested that they design a three-player game, each having the same set of pieces, consisting of prepared rectangles in different sizes. To specify each player’s pieces, they decided to paint each set with a different color (Figure 8). This, as they explained, differentiated their game from the original game, *Inversé*, being a two-player game and having blocks with various colors for both players. In the interview session,
they also pointed to how this feature of having three players distinguished their game from other redesigned games, and how they found this to be an optimum number of players for their game:

The researcher: Can you tell us about your game?
Sajan: So, our game is not like normal ... ours is more like a three-player version.
Sajan: Usually we play with two players but like our game is a three-player game.
The researcher: Why did you decide to have a three-player game?
Sajan: Because it’s kind of unique ... all games are like two players. And even in our class the people with three players use the whiteboard ((use dice and markers to draw pieces on a board)). But we don’t use the whiteboard, instead we just reuse the normal pieces and like the three players.
Talia: I think it’s kind of broken... because when we first did it, we tried two players, we tried four players but three became the maximum and the minimum. It’s kind of broken that way.
The researcher: So, three was a good number when you played?
Talia: Yeah.

Creating the pieces, Talia and Sajan cut six different rectangles for each player with different sizes (some were adopted from the Inversé’s blocks, and others were randomly determined). After discussing how they could come up with their board size with the teacher, Sajan decided to calculate the area of each piece and to sum the areas up. After doing “the biggest addition problem in this world,” as Sajan put it, he came up with the number 2166 as the area of the game board they needed. Although Talia speculated that this area would be too big for their game board, she and Sajan started to glue some grid pieces to create the board and try it.

Figure 8
*Extreme Versé: creating three sets of pieces*

*Markit: Using dice and adding randomness.* The group Markit started with Elena’s suggestion of using both dice and prepared pieces in their two-player game (Figure 9-a). Players
had to roll dice and then find the piece whose sides matched with the numbers on the dice. They prepared 4 pieces for each player (which did not cover all the possible combinations of numbers on their two 1-6 dice). When one of the researchers asked if the last person who could fit a piece on the board would win, Aaron explained, “like there are a lot of squares here ((showing a grid board)) and I got 2×2. So, if I put it here ((drawing a hypothetical square with his finger in the center of the board)), you will have no space anywhere.” They discussed how smaller or bigger boards could make players’ decisions on where to draw pieces more difficult or easier. After trying their initial idea of using both dice and prepared pieces, they moved to Aaron’s idea of using only dice and drawing pieces based on the numbers on the dice on their grid board, rather than using prepared pieces (Figure 9-b).

**Figure 9**

(a) Elena’s idea of using both dice and prepared pieces, (b) Aaron’s testing with dice and drawing pieces

Later, in our interview with the group, Elena talked about how she liked the idea of using dice. She explained that it differentiated their game from the games with a similar win condition (i.e., fitting the last piece on the board), that used prepared pieces for players to choose from. She described starting from the biggest piece as an easy access strategy for games with prepared pieces, as small pieces could fit more easily on the board at the end of the game: “I like the dice ...you always want to get the smallest pieces, but if you didn’t have the dice and you got to choose, then you’d always do a one by one ((from the biggest to the smallest piece)).” This showed how she saw the randomness the dice added could make deciding how to fit the pieces on the board more challenging.
Encountering various game dynamics and unfolding mathematical practices. Their interests in the games’ features (e.g., number of players, players’ pieces and play rules), therefore, engaged the groups with various mathematical concepts (e.g., use of area, multiplication, estimation, and randomness). Their ideas and decisions brought about different systems that set the ground for different game dynamics. With the decision of having three players, the group Extreme Versé encountered the complexity of having three players interacting instead of two. They needed to create more pieces and determine the board size accordingly. Their design process engaged them with the concept of area as an applicable concept in designing their game board and their game pieces (e.g., rather than the concept of perimeter). The application of area in their design engaged them with the use of numbers and multiplication. Their prepared pieces allowed players to have an idea of the resources, i.e., rectangles, they were going to use and their relative areas (Figure 10).

Figure 10
Extreme Versé: Players deciding about their moves using their set of rectangles

As Sajan explained, “(they) wanted their game to be based on strategy,” because if the game was based on luck and “you are unlucky you automatically lose the game.” They pursued this by not using dice and having the same set of prepared pieces for all players. They wanted players to strategize based on their estimation of the area of the empty spaces on the board and their rectangular pieces. Sajan’s approach was of course challenged later by Avani when reviewing the other students’ feedback on how their game needed “too much strategy.” She pointed to another group’s game which had used dice and mentioned how they could have incorporated “both luck and strategy” using different game elements: “the dice is luck and when you decide where you put (your piece) is strategy.”
On the other hand, the group *Markit’s* decision of using dice to create random pieces through the play, made the players face new situations each turn with less predictability. This could open the space for a more dynamic strategizing, compared to games with prepared pieces. This was partly reflected in Elena’s observation (quoted above) of the common strategy they could take in playing other groups’ games with prepared rectangles. As Aaron explained, they used numbers rolled on the dice, as the “side line” and “top line” of the pieces to be drawn. Deciding where to draw their rectangle needed them to have an estimation of the rectangle’s area using their rolled numbers. Through these mathematical practices, students applied, shared and tested their initial design ideas and went through a subsequent design decision for their games, which were further developed within their groups.

**Co-exploring meaningful play situations and creating more complex games.** The groups collaborated to incorporate different individual ideas and experiment with variations of their game pieces, boards, and rules. It led to co-exploring more challenging interaction situations and win conditions. The iterations of design, testing, and problem solving contributed to the emergence of unique designs and variations in the games.

**Revising the components to work in tandem.** The *Extreme Versé* group had a challenge with determining the size of the game board. They playtested their game with the big board they had made, with the principal researcher (Figure 11). In this later version of their game, players placed prepared pieces on empty spaces on the board in a way that same colors (i.e., a player’s own pieces) and same shapes would not touch (Figure 12). Therefore, players needed to consider both their own pieces (same color pieces) on the board and the opponents’ same size pieces when deciding where to fit their new piece. The last person to fit a piece was the winner.

**Figure 11**

*Extreme Versé: playtesting with the big size board*
During the play, Talia suggested they should have more pieces as the game was ending very quickly. After the playtest, they also had a conversation with the researcher about their board being too big (although they had used a board with a smaller area than their calculated area, 2166), which made fitting the pieces very easy. With their relatively big size board, there could be a tie situation, in which all the three players could place all their pieces on the board. The players would have too many empty spaces to strategize and estimate carefully to fit pieces. Talia came up with the idea of creating two game boards, with a smaller board for a harder version of their game and a bigger one for a basic version. As they were asked to come up with only one game, they finally decided to modify their current board to accommodate more meaningful decision making for players. Their method of creating the right size for their board was through testing smaller boards. They gradually cut down their board and tested how the game became more challenging using their prepared pieces, requiring careful estimation of the area to fit the pieces. We therefore observed that creating a more complex game led them to go beyond understanding their design challenge as a mere linear computation problem, unlike how Sajan had initially perceived in determining the board area. The mathematical thinking in this design project involved going through cycles of modeling ideas and exploring possible solutions, getting feedback and adapting the designs with their peers. This process also engaged them with multiple representations of the same math problem (English, 2006), as they used both symbolic representations and visual models (Figures 13 & 14-a) in creating their pieces and board.
Figure 13
Extreme Versé: (a) Part of Sajan’s calculations for determining the board size, based on adding the pieces areas, (b) checking the area of their pieces using a grid board

The following figures (Figure 14) also show their final steps in creating their board in which they were asked to use 10×10 grids. To do so they needed to determine how many full 10×10 grids would fit in their board and how to cover the rest of the board’s area with cuts of their grids. Figure 15 demonstrated their final board game and pieces.

Figure 14
Extreme Versé (a) creating their game board through gradually changing and testing the board size, (b) Making their final board using 10 by 10 grids and cardboard

Figure 15
Extreme Versé: The final board and game pieces
Balancing the game and exploring play situations. The Markit group had the challenge of creating a balance between chance and strategy. Their first version only needed players to roll dice to determine the length and width of their rectangular piece, draw the piece where they could find estimated spaces, and be the last one to fit a piece. Through playtesting with their teacher, they came up with the idea of using a smaller board or dice with bigger numbers, but they found this would not require players to use more strategies. Elena suggested adding one rule (Figure 16): “What if the pieces have to touch other pieces’ corners ((and only their corners and not their sides))?”. This idea added to the complexity of their game requiring players to strategize, based on the board condition and their random situation in each turn. It needed players to engage with mathematical thinking, including more conscious estimations and mental rotations.

Figure 16
Markit: adding the rule of corners’ touching

Elena playtested their new game with their teacher, while Aaron was watching their play. An episode of this session is provided in Table 4 to highlight how the interactions that were made possible through this playtesting could open the space for the teacher to explore students’ mathematical practices and their decisions as players of their own game. This allowed her to create relevant occasions to support students’ understanding of the math concepts of focus including area and estimation.
The teacher asked Elena about how she decided where to draw her new rectangle based on her rolled numbers of 5 and 1. She pointed to where she fit her rectangle and other spaces on the board she considered before drawing her piece:

Ms. Lennox: Why did you choose to do that?

Elena: Because I think I have much more space here ((pointing to where she drew)).

Ms. Lennox: So, it was easier to figure that out (to draw where you did)?

Elena confirms

In her turn, the teacher rolled 5 and 6. She used this as an opportunity to point out how considering the corner touching rule, she did not have many options to fit her big piece on the board:

Ms. Lennox: Oh, this one would be tricky. Because I can’t fit it on this corner ((pointing to one corner)) and can’t fit it here ((pointing to another corner))

but I can fit it there ((pointing where she intended to draw)).

The teacher draws her rectangle.
Elena rolled 3 and 6 and drew her new piece.

Ms. Lennox: Oh, Aaron what do you think she is doing ((pointing to Elena’s new rectangle))? 

Aaron: She kind of blocked.

Ms. Lennox: Yes, she blocked a little, but she touched two corners ((pointing to the two touching corners)). I guess she can get bonus points ((laughing)).

The principal researcher joined the group.

Researcher: So, you can touch any corner, doesn’t matter which rectangle?
The students showed how they would need to think if their piece fits. Aaron pointed to the small space surrounded by rectangles to show how the players would need to get small numbers to fit their piece there.

Aaron: ((pointing to the small central space))... a one.

Elena: or a two ((drawing a 1 by 2 rectangle on the board))

Researcher: oh, so a 1,1 or a 1,2. Yeah.
In the next turn, the teacher rolled 1 and 5. She seized this opportunity to build on Aron’s explanation on how if they get “1” they would not be able to fit their piece in the central area.

Ms. Lennox: So Aron, I rolled 1 and 5. Can I fit it here? ((pointing to the central empty part))
Aron: No.

Ms. Lennox: Oh, I see. So I need to make sure that both of my numbers are small to fit in the middle? ((Pointing to the two dice))
Aron: Yes.

After the next round of play, the teacher pointed to how the game is getting more challenging:

Ms. Lennox: Now it is getting a little bit trickier. Aaron, can you tell me why it is harder now?
Aron pointed to the empty spaces on the board and replied that there were not many pieces that could fit into the game anymore.

Games are modeled worlds that are enacted as they are shared with others participating as players. The design and playtesting process could provide various situations that make learners’ ways of thinking about the problems clearer to their peers and teacher. The interactions that took place in the process described above represented how learners playtesting their own designed games could occasion various possibilities for describing emergent situations using their own terms and various communicative modes (e.g., gestures, drawings and verbal expressions). This process helped the teacher explore students’ mathematical thinking leveraging on their design and play decisions. It also helped her notice students’ possible misconceptions or support them to clarify their explanations using more proper terms that mathematically made sense (Kim et al.,
As their conversation continued in their playtesting, Elena reflected that their game was taking too long. The teacher asked the group members’ opinion on what they could do to make the game shorter, which encouraged the group to explore more design possibilities using the elements they had already used and based on their understanding of how their game worked. Their suggestions included making their board smaller and using a bigger dice (i.e., with more numbers and sides) to add the possibility of drawing bigger pieces.

After their playtest with the teacher and subsequent reflections on their game, they decided to try a long and narrow board to make their game finish faster. The rule of touching the corner of drawn rectangles resulted in drawing rectangles in a row (Figure 17). Players, therefore, did not have many options to choose from in drawing their rectangles. In this round of playtesting with students from other groups, they used markers with different colors for the players to specify the rectangles by different players and calculated the area of each drawn piece and wrote them inside the rectangles. At the end of the game, they added the area of the pieces to determine the winner. Although this became a good practice in terms of multiplication for calculating area and addition, it made winning their game only based on the numbers players rolled, i.e., only based on luck and not needing players’ strategizing.

Figure 17

Markit: playtesting with a narrow board

Based on the feedback on how the game dynamic unfolded, the group decided to use a square-shaped board that provided more possibilities for drawing pieces, which only touched corners of already-drawn rectangles. Natalie and Aaron created their final board game using 10×10 grid papers and a thick cardboard (Figure 18-a). Based on their conversations on having
the rules that would allow for both chance and players’ decision making, they also switched back to the win condition of fitting the last piece on the board. Figure 18-b shows the group members playing their game with the laminated board and this final winning rule.

**Figure 18**  
*Markit: (a) making their square final board, (b) the group’s playing with their laminated board*

They then faced an optimization problem (i.e., deciding on an optimized board’s dimensions for this game) which encouraged them to test their game with different board sizes and shapes. The ongoing discussions about making a balance between chance and strategy, not only stimulated a common language for exchanging design ideas, but also engaged learners with more complex modeling problems. It subsequently triggered more unique collective design decisions and therefore more variations in the games. These observations also speak to the potentials of modeling practices in small groups in which individuals could find the space to express their conceptions of problems. Groups iteratively attend to “unstable and uncoordinated individual interpretations” and gradually develop “more coordinated, and increasingly stable group models” (Zawojewski et al., 2003, p. 350). Talking to the researchers about how simple games could become more complex through the design process, Elena used a remarkable analogy: “Kind of like a book, so it starts out with a word then it becomes sentences, then pages and then chapters.”

**Discussion**

This project contributes to supporting mathematics learning through modeling systems. The following discusses further the learning potential of this board game redesign project from a
complexity view and highlights how this analysis contributed to the second phase of my doctoral study, i.e., a complexity-informed learning design and analysis.

**Board game redesign for mathematics learning through the lens of enabling constraints**

The findings demonstrated that through the collaborative game design project students communicated their diverse ideas and used mathematical constructs to create interaction and play situations. Informed by a complexity perspective (Davis & Sumara, 2006), the analysis in this chapter showed how co-designing games could provide a platform for learners to pursue shared goals through which common design languages emerged. At the same time, it allowed the emergence of variations in students’ designs and use of mathematics. The process of game making encouraged students’ perspective taking, i.e., embracing their teammates’ diverse perspectives and the teacher’s and other groups’ feedback. It helped them communicate their design and mathematical ideas through multimodal exchanges, i.e., through use of gestures, movements, shapes and symbols in a physical space (Ferrara, 2014; Kim et al., 2021; Zawojewski et al., 2003). Through making decisions about game rules and meaningful play, they incorporated mathematical ideas and developed new insights as to what constitutes mathematics. This was exemplified in an occasion of providing feedback on the game *Extreme Versé*: students from two groups expressed their different interpretations of what it means for a game to involve mathematics. While one of the students believed that there is no math in the game without any explicit calculations, other students argued that there was math in the game when players would think where to put their pieces, as player decisions involved estimation and an understanding of area. This project provides insight as to how the view towards disciplinary knowledge and the practice of design for learning could reinforce each other. Perceiving mathematics learning as the mastery of skills imply a one-way relationship between the learner and knowledge, satisfying predefined curricular goals. Viewing mathematics as a tool to interpret phenomena and model systems, however, would reinforce the design for mathematics learning that allows for the participation of diverse ideas and new interpretations of systems around us. This would engage learners in using mathematical constructs to create meaningful systems that can be shared with others.

In redesigning *Inverse*, the groups experimented with a limited number of elements, e.g., rectangular pieces, dice, and a rectangular board, which supported developing a shared understanding of their developing design practices within and among the groups. The final
redesigned board games, however, showed the many possibilities that unfolded in terms of the games’ systems and play dynamics. These few elements along with the connected mathematical concepts became the material and tools for learners to think with and exchange various design ideas. Through choosing features of their interest and deciding about game rules, they created unique games. Learners went through rounds of mathematical practices involving the concepts of numbers, areas and estimation, as they pursued their interests and followed their dynamic design goals. We also observed how creating the game board became a significant phase in the design processes of the groups. It enabled the groups to make sense of the need for reevaluating the different components of their game system in relation to one another. They went through cycles of refining ideas and designs to set the ground for meaningful interactions and decision making in the modeled world of their game.

The evaluation of how individual ideas developed and converged into collective design ideas and group artifacts also shed light on group dynamics and control mechanisms. We specifically observed how students’ experience with and the perception of their relationship with the subject matter (i.e., mathematics), group work, and their teammates contributed to how they expressed their ideas and persisted the conversation around their viewpoints within their groups. Such elements could also be deeply intertwined with the social and cultural expectations perceived by learners (Sengupta et al., 2021). Mathematics and sciences education scholars have also highlighted the group dynamics that could hinder perspective taking and the interactions that involve multivocal explanations in group problem solving (Barron, 2003; Cobb et al., 2009). In this study, we observed how decision making and problem solving through the iterative process of game design and playtesting created some opportunities to interrupt the established patterns in students’ interactions and challenge the univocal groups. Further analysis on group dynamics could address how different patterns of group interactions could support or suppress the exploration of diverse ideas in groups, which is signified in complexity-informed accounts of design for learning. More specifically, future research could explore how the board game redesign approach for mathematics learning and its potential as practices of modeling systems could challenge the possible control mechanisms coming from the classroom authorities, the text, and peers, and what further structures could help the board game redesign approach move towards this aim. This endeavor would contribute further to how mathematics learning through collaborative redesign of board games set the ground for the complexity-informed conditions,
particularly in terms of enabling diversity and the possibility of supporting a decentralized control in student groups as emergent learning systems (Davis & Sumara, 2006).

**Using the findings towards the second phase of the research**

The findings from this analysis informed the next phase of my doctoral research, i.e., a complexity-informed design for learning. The board game redesign project in this mathematics learning study represented an open-ended task, with designed constraints, that can become increasingly more complex (Davis et al., 2015). This approach also speaks to the assertions on how the mathematical power of collaborative tasks relies on their appropriate level of complexity, in a sense that no individual group member can solve the problem on their own (Cohen, 1994; Zawojewski et al., 2003).

This analysis signified the importance of structured constraints at the starting point, which included students’ playing the same game and having the shared goal of redesigning it, in supporting a common language. At the same time, it indicated the interconnection of the constraining and enabling aspects of the developed commonalities throughout the process. Learners’ emerging idea exchanges at the class and group levels and reaching higher conceptual possibilities were enabled as they developed shared goals and understandings through the project structure and cycles of their unfolding co-design.

Notably, learners’ evolving interpretations of problems and possible solutions through the cycles of design and playtesting were intertwined with the emergence of co-constructed commonalities, as developing constraints (e.g., making their game balanced and incorporating specific game features), which stimulated specialized paths of using mathematics in groups.

The next chapter provides more details on how the discussed analysis contributed to the second phase of my study, i.e., a complexity-informed learning design and analysis. Besides attending to what was structured and what unfolded in this game redesign project (i.e., commonalities, diverse ideas, and groups’ variations in use of disciplinary knowledge), the analysis in the second phase aimed to more deeply explore how this approach could open the space for different ideas and interpretations to be expressed and the groups’ use of learning topics to evolve.
Conclusion

This chapter presented the findings from the first phase of my doctoral study, focused on a complexity-informed analysis. The analysis was to examine how collaborative redesign of a board game could support mathematics learning, using a complexity view of conditions to support learning. This analysis specifically explored how this learning design could support students to develop ideas on meaningful interactions in possible systems (i.e., games) and to collectively use mathematics to model those systems. The findings showed how co-designing games could provide a platform for learners to pursue shared goals through which common design languages emerged. At the same time, it opened the space for the emergence of variations in students’ use of mathematical constructs, in creating interaction and play situations and experimenting new possible structures in the modeled world of their game.
References


Chapter 5: Phase two, the Pandemic redesign project

This chapter discusses the second phase of the research in this dissertation. I describe the complexity-informed learning design in this phase and the analysis of students’ evolving design practices. Grade-7 students explored and created emergent systems (i.e., games) while redesigning the cooperative board game, Pandemic, using mathematics and science. As discussed in Chapter 2, this study attends to creating the settings for learners to develop commonalities, including shared language and goals, while supporting their varied ways of engaging with learning topics based on their interests and intentions. In connection with these complexity-informed conditions of design for learning, this chapter also addresses the notions of design space and self-imposed constraints from design and creativity research in analyzing the data to focus on the processes of students’ co-designs and their transformations. In this study, ethnographic data was collected through field notes and video recordings of students’ in-progress and final designs (more details on data collection are provided in Chapter 3). After a general description and analysis of the collaborative work of all the groups, this chapter uses the data from two groups of students and identifies the critical events that significantly contributed to the evolution of learners’ design space. The findings show how the game redesign activities and materials supported the divergence and convergence of ideas in various design episodes and how, through these episodes, learners’ conceptions of problems and design possibilities evolved. The opportunities for groups to use math and science topics emerged and expanded throughout the project. This was specifically intertwined with learners’ following their design goals and seeing more possibilities to implement their ideas to create a working system.

Learning design

The learning design in this phase is discussed in the following. The next section highlights how this design was informed by the analysis in phase one and the specifications of the implemented learning design based on the goals in phase two.

A design informed by the analysis of the Inversé project

The analysis of the Inversé project (Chapter 4) highlighted the potentials of using board game redesign based on the complexity-informed learning design conditions (Davis & Simmt, 2003); i.e., structuring commonalities for setting shared language and goals and supporting
learners to develop their own paths of engaging with disciplinary knowledge. It also signified the importance of complementarity between the learning settings (e.g., game design) and the content knowledge (e.g., mathematics) in order to support higher conceptual possibilities for students (Bastani & Kim, 2020). The following interconnected aspects summarize how the analysis in phase one informed the learning design in phase two of my research.

The analysis of the *Inversé* project indicated how the collaborative game redesign project became a platform for learners’ collective decision making and developing shared understandings and goals through which common design languages emerged. At the same time, it stimulated the emergence of variations in students’ designs and use of mathematics. The iterative process of game making encouraged students to embrace their teammates’ diverse perspectives and the feedback from the teacher and other groups.

The examination of students’ individual and group idea developments pointed to the potential of students’ collaboration in small size groups and having the possibility of sharing their ideas and artifacts within a larger-scale network of groups. Working in small groups would support group coherence and enable individuals to feel their agency and express their creativity in their shared projects (Zawojewski et al., 2003). At the same time, the anticipation of sharing their designs with others outside their group would encourage them to seek multiple viewpoints and design possibilities.

The analysis also highlighted learners’ opportunities to engage with mathematics, which evolved over time. The project’s constraints at the starting point mainly included playing *Inversé* and having the shared goal of redesigning it. This supported students’ common understandings of the original game and created a focus on the possible systems to be designed and the mathematical constructs to be used. At the same time, as the groups went through the design process, mathematically rich conversations were formed around the original game system and novel possible models. In this process, the teacher leveraged students’ emergent design goals to help them engage more deeply in using mathematics (Kim, Bastani & Takeuchi, 2021).

Finally, learners’ evolving design paths and the variations in their use of learning topics, their artifacts and their final design pointed to the role of groups’ co-constructed constraints in their work. Such constraints emerged as the groups went through cycles of design and playtesting, set new goals based on the specific game features they were interested in, and the
ways they aimed to use mathematics in their game and make their games playable and meaningful (e.g., making them balanced and embedding both strategy and chance elements).

**Adopting a board game redesign approach considering the learning goals of phase two**

As discussed in the second chapter (the positioning section), the study designed in phase two used complexity-informed conditions to design learning environments incorporating an integrated view of design for learning that would specifically attend to the learning content as an important design element that could reinforce the expression and interaction of learners’ diverse perspectives. The learning design conducted in this phase had a focus on engaging students with mathematics and science, mainly the topics of statistics and probability, and interactions and ecosystems, through exploring emergent phenomena. The approach of the partner teacher, a grade-7 mathematics teacher and a game designer, was also using creative projects that support interdisciplinary learning, not treating mathematics as an isolated subject matter, for his class. Based on these goals, some design elements were considered in adopting a board game redesign approach analyzed in phase one. Using a thematic board game that models an emergent real-world phenomenon was believed to open the space for students to use science topics in their game redesigns, besides the math topics of focus, and to explore the topics from multiple aspects and viewpoints. Evaluating different board games and their learning potentials, the cooperative board game *Pandemic* (Figure 19), which models disease spread across the world, was selected. As elaborated in Chapter 3, the decision on using a cooperative board game was mainly due to the complex structure of it and the interaction and collaboration space that could shape through cooperative play. Players’ need for externalizing their thinking process and collective strategizing (Berland & Lee, 2011), which is in contrast with the motivations in competitive games, could significantly contribute to their shared understanding of the game system. This could support learners in their game redesign projects, as they need learners to make sense of the original game’s rules and explore various play and strategizing possibilities. Besides, well-designed cooperative games would allow for multiple play trajectories and provide obstacles and complicated problems that reinforce players’ working together. The possibility of following different strategies in different rounds of gameplay also needs the game structure to both embody chance and allow for decision making (Seif El-Nasr et al., 2010; Zagal et al., 2006). This could make these games models of complex structures that allow for emergent outcomes.
It was expected that the theme and the system of the *Pandemic* board game (enacting disease spread) could engage students with exploring emergent phenomena, connected to grade-7 math and science topics (numbers, statistics and probability, and interactions, ecosystems and human impact). Importantly, the game’s inherent complexity could also engage learners’ diverse interests and stimulate various ideas and viewpoints, as learners explore its multiple components and possibilities of changing them (Bastani & Kim, 2021). It was expected that the math topics of focus (i.e., numbers, statistics and probability) could provide some structure (although loose) to their game designs and that their use of science topics emerge as they explore and decide on their game theme and develop their game backstory. Therefore, this phase of study conjectured that this learning design, compared to the *Inversé* project, could open the space for more variations in learners’ redesigned games as learners go through shaping their game theme and translating their ideas into game components, symbols, and rules.

**Figure 19**


**Collaboration with the teacher and implementation**

As elaborated in Chapter 3, the collaborative game redesign project was developed and implemented with a grade-7 math teacher (also a game designer), in Fall 2018 and early 2019 at an art immersion middle school in Alberta. The teacher was familiar with the *Pandemic* board game and saw significant learning opportunities in this game redesign project. He was also interested in working with the science teacher to make it an interdisciplinary project. He also suggested using the *Pandemic Iberia* board game, another version, i.e., an existing redesign, of
Pandemic, with a more geographic and historical focus in its theme. After the start of the project, the teacher asked one group, with their subsequent agreement, to redesign Pandemic Iberia.

As mentioned, the cooperative game Pandemic was chosen as the game to be redesigned in this project. In Pandemic, several viral diseases have broken out across the world and the goal is to collaboratively stop the spread and to find cures to eradicate these diseases. Players take unique roles, each having a specific strength to help this shared goal. The board has major cities across the world. Each turn, players have four actions which can be travelling between cities, treating an infected area, discovering a cure, or building a research station. There are two decks of cards. One deck would infect cities at a normal rate, and the other provides players with different abilities but also includes randomly distributed Epidemic cards which increase the infection rate and possibility of outbreaks. If a disease spreads to a point where recovery becomes impossible or if time runs out, all players lose. Players would all win if the cure for the four diseases are discovered.

Students worked on this project in small groups of 4-5 members. The following were the main stages of the project:

1) Playing Pandemic and mastering the rules (Figure 20);
2) Brainstorming possible changes and their game theme;
3) Narrowing down ideas for incorporating math and science with the teacher;
4) Designing and playtesting the game;
5) Inviting classmates and other classes to play the game; and
6) Reflecting on the project and thinking about future changes.

Table 2 in Chapter 3 shows these main stages (column 1) along with some description (column 2) and the design conjectures supporting each stage (column 3).

Figure 20

A gameplay session
Initial Analysis: Themes in the game redesign practices of the groups

This section discusses an initial analysis of data from this study. I provide a description of the board game redesign practices for each group. Despite the variations among groups’ design processes and final games, I observed two general themes that the groups’ game designs could fall into, which I address next. The group analysis, discussed after the initial analysis, focuses on two of the groups, one from each identified theme in this section, to explore and compare the processes they went through in this game redesign project more deeply.

Theme 1: Focusing on the original game system and making changes to it

Two groups of students chose to design a game with a theme and system more connected to the original game, Pandemic.

Pandemic- Canada Edition. The group Pandemic- Canada Edition, decided to have a game on disease spread in Canada: “because the original game had only one city from Canada” (One of the group members, Pandemic- Canada Edition, group interview). To create the game board, they used digital maps to locate the cities (Figure 21) and did some research on different contagious diseases specific to different cities in Canada (Figure 22-a). They designed their game mechanics, i.e., rules and components, with limited changes to the original game. They created their role cards based on some Canadian symbolic roles (e.g., hockey player and park ranger) using the software, Component Studio, which was suggested by their teacher. Intending to have a polished game by the deadline, they focused on this theme through the process without much deviation from it. They had an early draft and playtested their game with other students (Figure 22-b). This led to some modifications on the number of cities and their connection lines.

Figure 21
(a) & (b): Different episodes of using digital maps to locate the cities and create their map

(a) (b)
Reverse Pandemic. The other group, Reverse Pandemic, had the idea of reversing the goal of the original game. In their game, players acted as diseases that spread around the world (Figure 23-a) while the cities had different defence powers. This idea challenged the students to pay attention to the system of the original game and its rules and to research different bacteria and viruses and their survival mechanisms. Similar to Pandemic-Canada Edition, this group aimed to follow the deadlines and finish a playable game on time (Figure 23-b). They could playtest their game in their own group and with other students, which led to some modifications on how they connected the cities and the randomness in their game.

Although both groups, addressed above, built on the original game story and system, the changes they made differentiated the process they went through in terms of the complexity of
their design problems and the possibilities of using learning topics. The group *Reverse Pandemic*’s decision on reversing the original game’s logic required them to decode and modify the original game. In the design process, they also decided to have six players, i.e., six diseases instead of four in the original game, acting as players in their games. They also needed to look into how the cities, which were hotbeds for the different diseases, are grouped and coloured on the original game board and create a different graph based on their new grouping of the cities (Figure 24-a & b).

**Figure 24**

(a) New grouping of the cities, (b) Creating the map for their 6-player game

![Image of the cities](image1.png)

![Image of the map](image2.png)

The different design goals and decisions, therefore, led to different design problems, level of engagement with the original game system, and subsequent design decisions. The group *Pandemic- Canada Edition* changed the geographic locus of the game. This led to their geographical exploration of the country they live in and a symbolic design. They used similar game mechanics as the original game, which did not require them to deeply explore the connections among different rules and components and the game system in general. Of note, the project in this group was mostly managed by one of the group members, who was considered as an achiever at the school based on our conversation with the teacher. She had played the game *Pandemic* with her family multiple times before this project and was completely familiar with it. The lack of ambiguity and their focus on having a finished product on time could have contributed to the more straightforward procedure that they took confidently. At the same time, this hindered the group’s engagement with the exploration of various ideas and being exposed to more complexities in their designs.
Theme 2: Developing a new backstory for their cooperative game

The other three groups approached the project by designing new game backstories. These groups had a general understanding of the original game, being cooperative and network-based, which they used in their own game. They, however, needed to imagine new dynamics and therefore design new mechanisms for their game based on the backstories of their interest.

**Pandemic-Theatre Edition.** The group *Pandemic-Theatre Edition* came up with the backstory of creating a balance in the world, through the cooperation of different roles and powers (e.g., an environmentalist, an actor, a scientist) (Figure 25-a). They discussed the imbalance in the world in terms of environmental conditions (mainly hot vs. cold regions) and imagined creating a balance by moving the residents of these areas between each other. They symbolized the residents of different regions with sad people and “overly happy” people who did not care about the environment.

Their backstory was specifically connected to the “interactions and ecosystems” topic in their science curriculum. They also used “statistics” in designing the rules for moving people to different areas on the map (Figure 25-b). It was noticeable how their game’s main theme, i.e., creating a balance in the world, acted as their design big picture or frame, and how through the project they explored its different aspects (e.g., how to determine hot/cold and sad/happy regions in the world). They also iteratively evaluated possibilities of translating their game story elements into game mechanics (e.g., how to move people between the regions). By the project’s deadline, they could implement the main ideas and play their game with other students but were still in the process of making their game more complex and meaningful. This made having a well-crafted game system challenging for them.

**Figure 25**

(a) Creating the role cards, (b) the game’s map
**Collapsed.** Another group, *Collapsed*, developed a backstory about an unexpected mixing of the DNAs of two animals leading to the creation of an invasive species (Figure 26- a & b). This species would eat some other species three times faster than usual. This leads to a disruption in the food web (Figure 27), i.e., the extinction of some species and the overpopulation of some others: “if one animal goes away ... it like disrupts (the food web), because one animal gets overpopulated and one animal starts dying out” (Karen, one of the group members). The goal of the game was for human beings to save the world from this disruption. This idea was specifically connected to the topics of food web and human impact addressed in their science class:

Our science teacher told us how humans could save the world if we wanted to or completely destroy it. So, in this case, we kind of destroyed it but then we re-saved it.... Turning it into a game is how we save it which shows how humans can save the world if they choose to. (Karen, Interview session)

**Figure 26**

(a) Creating the invasive species character, (b) Creating the digital model of the invasive species

This engaged them with researching different species and using a food web in designing the graph on their board game (Figure 27).

**Figure 27**

*Collapsed-The designed web on their game board*
The complexity of their backstory led to various individual ideas on different aspects of their game’s theme and mechanisms, e.g., saving the species by finding ways to breed the endangered animals, determining which animal to save first considering the food chain, and having indicators for a critical level of extinction or development of invasive species (passing a certain amount would lead to losing the game). In the interview session, one of the students, Karen, talked extensively about their ideas, including the ones they could not implement. She mentioned how each idea required a sequence of changes in their design: “if you add one small detail, you actually have to change a lot of the rules which is what we found out…. We had so many ideas it was hard to think of which ones to add in the game.”

Their ongoing idea development and research led them to revisit and expand their story and design with the goal of sharing and playing their game with others. Karen viewed this goal as what differentiated this project from their other creative projects:

We have done really big things, but we’ve never done a thing where we had to design something that’s like it’s the thing that people are going to use…. You would have to think about how it benefits other people and how they’ll be able to use it. When you do a statue project you don’t have to think about that. You only have to think about structure. But in this, you have to think about everything, what kind of strategies there could be. Although their ideas could not converge into a coherent game rule set within the project timeline, their imagined game space and design goals engaged them with an exploration of learning topics, mainly science topics. Simultaneously, it could help them make sense of the learning topics as relevant and useful in developing their designs: “The science for sure is very interesting. I loved adding in science and thinking of new ideas all the time. … Each new class we had with science and math that would make us get more ideas” (Karen, interview session).

**Mauritius Pandemic.** As mentioned in the previous sections, one of the groups played *Pandemic Iberia*, a version of *Pandemic* with a historical and geographic focus (Figures 28-a & b). *Pandemic Iberia*’s story happens in the mid-19th century in the Iberian Peninsula where the four diseases of malaria, typhus, cholera, and yellow fever are spreading among the cities. Players take different roles, e.g., a doctor and an agronomist, to research the diseases and stop their spread.
Similar to *Pandemic Iberia*, this group’s game story had specific time and geographic context. They decided to focus on Mauritius island (Figure 29) when its extinct species still existed. They changed the game's goal to save the animals living on that island from extinction.

In the interview session, with the presence of all the group members, the students talked about their game idea and the research opportunities and challenges in the process. One of the students explained,

> Instead of infection cards we replaced it with extinction cards and then the plot of the game is, ...we are going back in time, extinct animals are not extinct yet such as the dodo bird. ... They are still here and your job is to prevent them from going extinct. So, by
doing that you basically need to go around and figure out why the creatures might be
going extinct and then stop that. (June, interview session)

They developed the idea of using today’s knowledge and technology to prevent the
extinction of animals in Mauritius Island. Therefore, they imagined creating a situation in which
players do some research on the local animals and travel back in time to prevent them from
extinction:

We had two different kinds of problems. The first one was that the dodo bird went extinct
in the past. ... And you couldn’t really bring it back or like fix it in the past because you
didn’t have the technology so then you’d have to go in the future or in the present time ...
so we decided to travel back. (Anna, interview session)

While they were researching the local animals, their living conditions and the human
impact on their habitat and their extinction (e.g., Figure 30), they spent a considerable time
designing their board and their cards in multiple sessions to represent the island condition and
the animals’ habitats (Figure 31).

**Figure 30**
*Researching different areas on Mauritius Island*

**Figure 31**
*(a) Designing the board, (b) Making the game cards*
They had a focus on using biology and human impact in their science curriculum. By the end of the project (figure 32), although they acknowledged their problem with time management, they talked about the research opportunities this project provided for them, which were of their individual or group interest, and the problems they engaged with as they developed their design:

We ... learned a lot through the process of researching ... like when we would look up an animal that we didn’t know is on Mauritius originally, we ... learned like interesting facts about their life ... like how they live and like their process (of evolution) through the world. (June, interview session)

**Figure 32**

*The version of the game used on the play day*

In their game redesign process, therefore, the group engaged with reenacting complex situations through reevaluating the dual impact of humans on the environment and reimagining possible scenarios for playing a role in saving other species. Their geographic and historic focus, informed by the *Pandemic Iberia* board game, acted as a frame for their idea development and supported their group coherence in researching the areas that could help in developing their game theme. Their geographic focus and having the goal of preventing species extinction led them to do extensive research. They explained that,

You know how ... there was maybe at least 20- animal species that went extinct like famous ones... Mauritius is ... tiny. If this ((pointing to their map)) was the whole (world) map, it ((Mauritius island)) would be this little dot. And imagine how many animals in the whole entire world there would be. There’s like a hundred over here and that’s (only) Mauritius. (Anna)

Their research involved more complex topics, such as how humans could disrupt an ecosystem. They explained how Mauritius being a popular hub for sailors put the lives of species
at risk:

(Sailors) would travel down there and they would come across this island. And that was probably the reason why there was so much extinction going on the island. Because there were no predators, so everyone was literally friend with everyone and everyone was a herbivore there. (Jacob, interview session)

Their design process and reflections of the project showed how this project could extend the horizon of possibilities for this group’s active engagement with complex issues involving the human condition in the world. Their geographic-historic focus enabled them to develop a shared understanding of their design goals and expand and deepen their research on the topics of their interest that they aimed to incorporate in their game.

**Commonalities and variations among the design process of different groups**

The general analysis of the groups’ design projects highlighted commonalities in the groups’ work processes and variations in their design trajectories. It was notable how the designed games shared a consideration of interactions in an elaborate context in their narratives and a network-based structure in their systems, which was connected to the purposes behind selecting the board game *Pandemic*. The groups used mathematics at different levels in implementing their game and designing the components. The original game and redesigned games were thematic which opened the space for using the science topics and expanding the research on the different aspects of the areas of their interest in the game backstory and system. This could promote opportunities for making a meaningful relationship with disciplinary and interdisciplinary knowledge as was reflected on by some of the students.

On the other hand, the varieties among all the groups’ games and differences in design approaches and practices within each identified general theme in this analysis were notable. The *Pandemic* game’s theme and system are complex. It was, then, expected that as learners build upon their understanding of this game, they could imagine and create diverse game narratives and structures and engage with the learning topics in their own ways. As the groups engaged in the design process, I observed how certain approaches and decisions acted as constraints that both limited the scope of their work and opened up possibilities of idea development. The groups’ decisions and choices shaped the critical episodes through which their ideas and designs evolved. Importantly, some of the groups could develop rough copies of their game as their materialized ideas and decisions that helped them receive feedback and reflect on their own
designs.

Reflecting on students’ collaborative designs in our interview, the teacher particularly pointed to how some of the groups’ “strong focus of the beginning,” such as the geographical focus of the Mauritius island group or the decision of reversing the logic of Pandemic by the Reverse Pandemic group, made the complex project of game design more accessible to them. As the teacher put it, their focus acted as an “isolating layer” that students could start their design with and build upon to have a more complex game. The following section on group analysis further attends to the process of students’ idea development and the role of constraints in shaping and transforming their designs.

**Group Analysis**

The analysis in this section focuses on one group in each identified theme in the initial analysis. This group analysis aims at a more detailed exploration of learners’ game redesign processes and the underlying elements that stimulated their collective idea development and engagement with learning topics, in addressing the research questions: 1) how would learners’ co-design practices evolve through the redesign process? and 2) how would learners’ decisions, ideas and interests frame their designs and open the space for using math and science in creating game systems?

I discuss the analysis framework and provide examples of how data was chunked into meaningful episodes that represent how the interaction of learners’ ideas, materials and activities transformed their collective designs.

The findings elaborate on the identified critical episodes of students’ design practices to address the research questions.

**The analytic frame**

In framing my analysis of the evolution of learners’ practices and understandings in their game redesign project, I draw on the notion of design space and self-imposed constraint from design and creativity research (Biskjaer & Halskov, 2014; Stokes, 2001) in connection with the notion of enabling constraints (Davis & Simmt, 2003). The analytic frame in this phase attends to the divergence and convergence of ideas to explore learners’ transforming design spaces.
Enabling constraints and the potentials of design practices. Complexity views have discussed the conditions that could stimulate more learning possibilities for learners. They use the notion of enabling constraints to indicate how design for learning should attend to a balance between setting structures, which would limit the vast possibilities of approaching learning topics and support learners’ shared goals and language, and enabling learners’ different responses and pursuit of interests (Davis & Sumara, 2006). This approach is rooted in a view towards emergent systems that are “rule-bound” and constrained but are also flexible and capable of “unanticipated possibilities” (Davis et al., 2015, p. 219).

The research on design and creativity has also discussed different aspects of design practices that point to their value in supporting learning. They include decision making, adapting to evolving goals, imagining and examining various alternatives, and therefore embracing multiple viewpoints. Importantly and in line with the notion of enabling constraints, the literature on design signifies the importance of constraints in the process of design as they could prompt a pathway to creativity and innovation (e.g., Sternberg & Kaufman, 2010; Stokes, 2009). They include external constraints such as materials and time limitations, and self-imposed constraints that emerge as designers’ different ideas interact and lead to design decisions. Design is about initiating change and creating new things or reforming what exists based on human agency. It is the intentionality interwoven into design that uses the abstract scientific knowledge and transforms ideas into a unique design that manifests itself in the world (Biskjaer & Halskov, 2014; Nelson & Stolterman, 2014). With every decision, designers impose some constraints on their work that not only restrain the next actions but also become tools to think with and to explore new possibilities. Therefore, a co-evolution of problems, goals, and possibilities happens in the process of design (Biskjaer & Halskov, 2014).

Exploring the evolution of the design process. To explore how design possibilities emerge and evolve, design scholars have explored the design process through the notion of design space (Biskjaer et al., 2014). Design space in a broad sense is a dynamic conceptual space of possibilities that is constructed as designers go through the design process. Building on Schön (1992), systemic perspectives describe the design space as continuously developing through the interactions of designers and design conditions. Designers begin with their experience and knowledge resources and develop a dynamic understanding of the design situation encountering design constraints and making decisions that frame their work (Olesen & Halskov, 2018). They,
therefore, depict the design process as a continuous space of experimentation and reflection. To explore the complex process of unfolding design possibilities, in which designers’ views of problems and solutions evolve, scholars have suggested documenting the events that signify the temporal interplay of designers’ decisions and design goals, constraints and opportunities. Others have argued for attending to the stimuli of the emergence of ideas and decision making, such as materials and types of interactions and activities, in order to support and analyze the design practices of student designers (Hutchinson & Tracey, 2015).

**Divergence and convergence of ideas in the transformation of the design space.** To make sense of the design process scholars point to the cycles of divergent thinking, i.e., exploring various possibilities and ideation to go beyond the immediate design space, and convergent thinking, i.e., choosing from and reducing alternatives to come to a more focused understanding of a problem or arriving at a solution. Through the cycles of divergence and convergence of ideas the design space would transform and so would the designers’ conceptions of problems and possible solutions (Biskjaer et al., 2014; Finke et al., 1996; Norman, 2013).

Based on the above discussion, the analysis frame in this phase attends to divergence and convergence of ideas that happen iteratively in the design process (Norman, 2013) and the role of constraints (Onarheim & Biskjaer, 2017), including the activities structure and learners’ self-imposed constraints, in these cycles and transforming the design space. Importantly, self-imposed constraints are evolving frames that could open the space for designers’ further exploration. Through identifying the occasions of imposing constraints in the design process, I mainly investigate how learners’ interests and intentional choices enabled them to develop their designs and expand and deepen their use of learning topics. Within this frame, the analysis attends to how the interaction of learners’ ideas and goals and game design materials and activities supported their decision making and transforming their designs.

The model provided below (Figure 33), on the analysis framework, adopts the *double diamond model of design* (Norman, 2013), focusing on divergence and convergence of ideas, while highlighting the iterative nature of design.

**Figure 33**

*The analysis framework model*
The process of interpreting data

The group analysis in this phase uses the data from one group in each identified theme in the general analysis, namely the Reverse Pandemic group and the Pandemic- Theatre Edition group. This selection was mainly based on having data collection consent from the group members (and their parents or guardians) and having more comprehensive data from their design process. Similar data collection methods and procedures were used for all the groups, while considering not to collect data from the students who had not consented. However, some of the groups’ discussions and designs took place in occasional sessions out of the math classes where data was collected from. Reviewing the field notes and the video data after the project led to a final selection of these two groups for this analysis.

The procedure of organizing data. The organization and coding of data in this section is informed by Barab et al.’s (2001) process for “capturing and tracing the emergence, evolution, and diffusion of a practice, conceptual understanding, resource, or student-constructed artifact” (p. 63). This approach involves identifying the critical episodes or “chunks of meaning” (p. 74), in which learners’ idea development and practices evolve, through their interactions with one another and with the tools and activities, and finding links among these episodes with the goal of addressing the research questions. I found this approach specifically in line with this study’s view of students’ understanding and practice as situated and emergent, and useful in addressing the analysis framework focusing on the changes in learners’ group work process. As Barab et al. (2001) discussed, through this process,
(researchers could) identify relevant data from a complex, evolving environment, and then organize it into a web of meaning that can illuminate the emergence and historical development of various practices, concepts, resources, and artifacts occurring over extended time frames, as well as the potential of a particular environment for supporting these processes. (pp. 105-106)

The analysis framework was used in chunking the data from the groups. I identified the episodes of the groups’ idea development and changes in their conceptions of problems and possible design solutions through their game redesign practices. To address the first research question, this analysis seeks the temporal links among the emergent critical episodes and, therefore, how learners’ co-design practices evolved throughout this project.

Addressing the second research question, the analysis attends to students’ interests and interim decision makings and how they contributed to the groups developing their designs and using learning topics. It explores the links between the tools and activities involved in the game redesign project and students’ decision making and idea development.

Table 5 demonstrates an example of how the data was chunked to indicate the critical episodes and their different aspects identified through coding of video transcripts based on the framework. It signifies the elements in students’ discussions showing the divergence of ideas, the elements showing the convergence of ideas, and the settings of their emergence (the complete table for the groups of focus is provided in the findings section).

Table 5

Examples of identified critical episodes (Reverse Pandemic)

<table>
<thead>
<tr>
<th>Episode</th>
<th>Divergence Elements</th>
<th>Supporting Interactions</th>
<th>Convergence Elements</th>
<th>Supporting Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taking the perspective of bacteria and viruses</td>
<td>Exploring how bacteria and viruses spread and act in different environments and the human mechanisms of defending against diseases</td>
<td>Discussing their game story and goal with their science teacher/ using Pandemic’s board to discuss their game ideas and discussing disease spread</td>
<td>Discussing the mechanisms that could strengthen or weaken players (i.e., diseases)/ deciding what diseases they want to use in their game/ developing rules of players’ actions and cards (diseases cards)</td>
<td>Researching bacteria and viruses on the Internet/ drawing diseases cards/ making parallels between their intended game components and the original game’s components/ discussing their implementation plan with their math teacher</td>
</tr>
</tbody>
</table>
Using Numbers, percentages and probability as a tool to materialize ideas

Exploring how to integrate the connected math topics (numbers, statistics and probability) in their game

Evaluating the original games’ cards and their roles in the game, mainly how probability is used

Used numbers to determine players’ power (disease spread) against cities’ defence (CD)/ designed vaccination cards, using probability, which made cities’ defence dynamic

Working together to make the City Defence, players and vaccination cards (one out of ten players cards were vaccination cards)

Encountering complexities in balancing the game

The groups exploring the reasons of power imbalance in their game (players, i.e., diseases could not win)

The groups playtesting the game/
Reevaluating Pandemic’s components

Evaluating how to give some advantage to players/ Making their game based on both chance and strategy to make it playable (e.g., adding random virus bases)/ deciding the ways players may lose

Exploring the mechanisms in Pandemic that create a power balance (e.g., unexpected events)/ Playing their own game

Table 6 also exemplifies the main aspects in each episode that could contribute to transforming the groups’ design space and the constraints involved in this process.

**Table 6**

*An example of the analysis of the critical episodes’ transforming aspects and the constraints involved (Reverse Pandemic)*

<table>
<thead>
<tr>
<th>Critical Episode</th>
<th>Transforming aspects</th>
<th>Constraints involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taking the perspective of bacteria and</td>
<td>Learners’ practices becoming more focused and purposeful</td>
<td>The group decision of reversing Pandemic’s story</td>
</tr>
<tr>
<td>viruses</td>
<td>Developing their game backstory and system through exploring how bacteria and viruses</td>
<td>The need to translate their story into game mechanics</td>
</tr>
<tr>
<td></td>
<td>act</td>
<td></td>
</tr>
<tr>
<td>Using Numbers, percentages and</td>
<td>Decoding and modifying the original game mechanisms (e.g., the probability of</td>
<td>The project goal of using mathematics</td>
</tr>
<tr>
<td>probability as a tool to materialize</td>
<td>epidemics)</td>
<td></td>
</tr>
<tr>
<td>ideas</td>
<td>Using different mathematics topics in creating the game dynamics and rules</td>
<td>The group’s decision on using specific topics connected to the Pandemic game’s system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encountering complexities in balancing</td>
<td>Making a deeper sense of the interconnections in the original game (the role of</td>
<td>Project deadline</td>
</tr>
<tr>
<td>the game</td>
<td>random events in giving advantage to players)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Encountering the role of randomness in making their game system balanced</td>
<td>The group goal of having a playable game</td>
</tr>
<tr>
<td></td>
<td>All the group members expressing their ideas on different aspects of their game (e.g.,</td>
<td>Intending to have a balanced game</td>
</tr>
<tr>
<td></td>
<td>how to make it balanced, how to modify the graph on the board)</td>
<td></td>
</tr>
</tbody>
</table>
Findings

This analysis attempted to understand how design and learning possibilities unfolded as learners went through this board game redesign process. In the following, I discuss the redesign effort of two groups, whose redesigned games were named *Reverse Pandemic* and *Pandemic- Theatre Edition*. Elaborating on the identified critical episodes of students’ design practices, I address how learners could expand their ideas over time, transform their conceptions of problems and design possibilities, and find opportunities to research on and use learning topics. This involves discussing how the interaction of learners’ ideas and goals, materials and activities supported their decision making and transforming their designs.

*Reverse Pandemic: Players acting as viral diseases*

This section discusses the findings from the analysis of the game redesign practices of one of the groups in the first theme identified in the general analysis, namely, *Reverse Pandemic*. The following subsections present the critical emergent episodes identified in the analysis of this group’s game redesign. Table 7, at the end of this section, also provides a summary of the critical episodes along with the elements of divergence and convergence of ideas and the supporting settings in each episode.

**Developing the game theme and goal.** After brainstorming and evaluating different paths of redesigning the game (Figure 34), the group developed the idea of reversing the *Pandemic* game story, i.e., creating a cooperative game in which players would act as diseases trying to overtake the cities and spread around the world.

**Figure 34**

*The group brainstorming using an idea sheet*
In a session for narrowing down ideas, they explained their ideas, including their discussed game theme and goal and possible connections to the learning topics to their teacher. As he inquired about their ideas, the teacher took note of their overall approach to their redesigned game. This step supported the group to develop a consensus and shared understanding of their design goal, which shaped a direction for this group’s design process. One significant aspect of this group decision was their building on the original game’s narrative, and not changing the game’s theme completely. This decision was followed by discussions on how to design their game elements and connect the game to learning topics. The Pandemic’s physical game materials, e.g., the cubes representing viruses, board map, and infection and role cards, mediated the group discussions (Figure 35) on the different aspects of their game and possibilities of implementing their ideas, as exemplified in the following conversation:

Elaine: We are doing a reverse pandemic.
Jess: Let’s look into it a little bit more. So, these ((pointing to the cubes representing diseases in Pandemic- Figure 3-a)) will be …
Elaine: will be like cures.
Jess: And we have to try to overpower cures. … You have to collect multiple cards of the same colour ((pointing to city cards used to cure diseases in Pandemic- Figure 3-b)), like if I get two (cards) and there are two yellow (cubes) on here ((pointing to a city on the board)) I can go to that place ((to remove those cubes)).

Figure 35
(a) & (b): Episodes of students using the original game’s components to discuss their ideas

It was notable how, in their initial dialogue, they were trying to implement their idea of reversing Pandemic’s story by defining opposite functions for the original game’s components (e.g., cubes representing cures instead of diseases) (Turn 1-4). This approach, however, might
not be helpful in reversing the dynamics of a game system. For example, in *Pandemic*, the cubes represent the number of infected areas on the map and the possibility of outbreaks. Therefore, simply using them to represent cures would not make meaningful cure dynamics in the redesigned game. This step was still a significant step toward a deeper exploration of the original game system.

At this stage, they also talked briefly about how *Pandemic* is connected to the topics in their science class, i.e., environments and ecosystems, and bacteria and viruses, as the game involves different places in the world, and viral diseases.

**Taking the perspective of bacteria and viruses: Developing the game’s backstory and system.** Students’ focus and practices evolved and became more purposeful as they started evaluating the possibilities of implementing their initial ideas while using and creating different game components and rules. A transforming event happened for the group when they shared their ideas with their science teacher. They had a conversation about the theme and rules of *Pandemic* and the group’s ideas of reversing the theme. It started with a question by Jess, one of the group members, asking “how players (diseases) could move ((on the board)) and overcome the cities in their game” and led to elaborating their game backstory and system.

Their chosen game theme, as a self-imposed constraint, encouraged them to take the perspective of bacteria and viruses, exploring the mechanisms that players could progress through spreading diseases. The conversation centered around how bacteria could develop resistance against antibiotics and mutate and evolve, and how they spread. As they discussed, Jess suggested they could use the containment meter (in *Pandemic*) and move it backward to show the progress of cures. The teacher talked about how diseases spread as the group explained how the original game worked, showing him the original game’s elements and their game ideas.

The teacher built on Elaine’s discussion on players (diseases) moving between the cities, using the *Pandemic* game board, and explained how a disease could spread to far away locations due to international travels: “one of the biggest issues with our global community is we travel a lot. An infection that happens in Chicago can easily end up in Jakarta in a day. And then you will have two outbreaks ((pointing to the map))” (Figure 36) (it should be noted that these discussions during the game design project happened before the spread of Covid-19 and the widespread knowledge about pandemics). Taking the perspective of diseases, they then talked about how travelling between cities could be an advantage for players. Discussing the possible defence
mechanisms against diseases for cities, they also talked about how making new vaccines could cause widespread and long-term immunity. Students also discussed how the diseases could act differently in different environments, connecting it to the cities’ defence power against diseases in their game, as we can see in Jess’s remark: “Would the disease become different if it was in a different environment, based on the temperature? … that could impact the City Defence”.

**Figure 36**

*(a) Discussing disease spread using the board, (b) talking about possible emergent outbreaks in two distant locations*

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I observed an intentional interaction between students and teachers mediated by the game materials (Kim et al., 2019), e.g., the board map and other game components, which supported the integration of learning topics. Their design space with the goal of reversing the theme of *Pandemic*, therefore, changed to include more scientific exploration. Their taking the perspective of viruses enriched their game backstory and expanded their view of what is possible in designing different game components in a meaningful and connected way (e.g., how players – diseases – could take advantage of moving between cities, and, at the same time, how it could be disrupted by other mechanisms such as vaccination). After their discussion with the teacher, they researched different viruses and bacteria and decided which one to use in their game. They started working on implementing their idea of overcoming the cities based on the cities’ protection level. They also developed their player cards (Figure 37), their infection cards, and the rules of players moving among the cities, i.e., how diseases would spread among the cities.
**Numbers, percentages and probability as a tool in materializing ideas.** The group soon found that to reverse the story of *Pandemic*, they needed to understand this game’s system more deeply. They evaluated how infection cards, which determined which cities to be infected based on designed probabilities, work and how epidemic cards could trigger an outbreak. Put differently, their choice of reversing the *Pandemic*’s story became about reversing the logic of this game, rather than reversing the role of elements in this game. This self-imposed constraint involved making sense of new possibilities of using math in creating a playable game. Their design problem evolved and so did their choices and design space. Their exploration of using math in their game converged, at this stage, into using numbers to compare players’ power (disease spread) against cities’ defence (CD). Jess explained players’ attack and cities’ immunity and defence mechanisms:

> The players also have their defence, not defence but their strength of attacking… it just says PP instead of CD for player probability and then it will have a number as well. So, if yours is high ((higher than the defence card)) you will take over… and if the city’s is higher, then you just discard that and put it under the bottom again, because we ((players or diseases)) have to keep moving on because we are not strong enough.

They also designed vaccination cards (Figure 38), using probability (one out of ten player cards were vaccination cards), which made cities’ defence dynamic: “The city defence changes when 70 percent of the population get vaccination” (Jess).
Incorporating the features of their interest in their game. In the design process, the group decided to have six players, making their game different from *Pandemic* that involves four diseases. They, therefore, needed to have six diseases (instead of the four diseases in *Pandemic*). This decision needed them to make changes in categorizing the cities that were hotbeds for the different diseases (Figure 39-a): “we are going to divide them ((cities)) by 6 instead of 4 because... it is kind of confusing because there is 6 different roles or seven in *Pandemic*, but we want to have 6 but we are going to be the diseases instead of roles ((players’ roles in *Pandemic* trying to stop diseases)) ... we don’t want it to be only a 4-player game” (Jess, in a conversation with the researcher). Through grouping the cities, they were also engaged with the geographical aspect of *Pandemic*, locating the cities on the map, discussing how to scale down the map and create one for their own game. Their exploration of how to have a 6-player game, then, converged into drawing their own map. This became a challenge of how to connect the cities based on their game goal and designed system. They, therefore, faced a “graph” problem in creating their cities’ network (Figure 39-b).

**Figure 39**
(a) Designing the board, deciding how to connect the cities, (b) Creating their final board based on having 6 players (new grouping of the cities)
Encountering complexities in balancing the game. Having a draft of their game in time, the group could playtest their game. During playtesting (Figure 40), they found that in their initial design, diseases (players) could not win. They reevaluated Pandemic’s components and noticed how Event cards, which would give players random advantages, created a power balance (e.g., the ability to predict which cities will be infected next). In their redesigned game, they had created vaccination cards that would give advantage to cities against players (diseases), but they had not used enough mechanisms to give players random advantages. They then designed their own event cards that would randomly allow players (diseases) to make “virus bases” in other cities to travel between them and spread. The group’s intention of having a balanced and playable game, therefore, led them to make a better sense of the interconnection of different elements in the original game and incorporate their understanding in their own designs, in a way that was meaningful to the narrative and dynamics of their redesigned game.

Figure 40
Playtesting their designed game

I observed that, compared to other groups, this group had the goal of having early, playable drafts to finish a well-crafted game. Having a special focus on project deadlines, they could have a playable game that they could test and get feedback on. Similar to what Kim et al. (2019) argued, as students shared their work and confronted their own designs with their applications in the world, they could experience the problems in context and attend to further possibilities. They could develop a more holistic view and see more complex interconnections. Their more complex understanding was specifically supported through the exchange of group members’ diverse viewpoints, as their playtesting needed the active participation of the members. It enabled them to express their ideas on different aspects of their game, e.g., how to create a power balance, how to modify the graph on their board according to their game goal, and how to make their game meaningfully more complex.
<table>
<thead>
<tr>
<th>Episode</th>
<th>Divergence Elements</th>
<th>Supporting Interactions</th>
<th>Convergence Elements</th>
<th>Supporting Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing the game theme and goal</td>
<td>Initial brainstorming</td>
<td>Group discussion/ working on an idea sheet</td>
<td>Narrowing down the ideas/ the group’s consensus on the theme; i.e., players acting as diseases (reversing the original game’s theme)</td>
<td>Students discussing their ideas with the teacher/ teachers asking about their game story and goal and the connected learning topics</td>
</tr>
<tr>
<td>Taking the perspective of bacteria and viruses: Developing the game’s backstory</td>
<td>Exploring how bacteria and viruses spread and act in different environments and the human mechanisms of defending against diseases</td>
<td>Discussing their game story and goal with their science teacher/ using Pandemic’s game board to discuss their game ideas and disease spread</td>
<td>Discussing the mechanisms that could strengthen or weaken players (i.e., diseases)/ deciding what diseases they want to use in their game/ developing rules of players’ actions and cards (diseases cards)</td>
<td>Researching bacteria and viruses on the Internet/ drawing diseases cards/ making parallels between their intended game components and the original game’s components/ discussing their implementation plan with their math teacher</td>
</tr>
<tr>
<td>Adding unique features to their game</td>
<td>Evaluating how to have 6 players, and how to group the countries and draw their board to implement that idea</td>
<td>Examining the original game’s rules and map/ Discussing how to connect the cities</td>
<td>Scaling down the original board’s map and locating and connecting the cities based on the grouping system they came up with</td>
<td>Grouping the cities on a sheet / exploring how the cities are connected on the Pandemics’ map/ discussing how to scale down the map/ drawing their map using the Pandemic’ board and their own groups of cities</td>
</tr>
<tr>
<td>Using numbers, percentages and probability as a tool to materialize ideas</td>
<td>Exploring how to integrate the connected math topics (numbers, statistics and probability) in their game</td>
<td>Evaluating the original games’ cards and their roles in the game, mainly how probability is used</td>
<td>Used numbers to determine players’ power (disease spread) against cities’ defence (CD)/ designed vaccination cards, using probability, which made cities’ defence dynamic</td>
<td>Working together to make the City Defence, players’ and vaccination cards (one out of ten players’ cards were vaccination cards)</td>
</tr>
<tr>
<td>Encountering complexities in balancing the game</td>
<td>The group exploring the reasons for power imbalance in their game (players, i.e., diseases could not win)</td>
<td>The group playtesting the game/ Reevaluating Pandemic’s components</td>
<td>Evaluating how to add advantage to players/ Making their game based on both chance and strategy to make it playable (e.g., adding random virus bases)/ deciding the ways players may lose</td>
<td>Exploring the mechanisms in Pandemic that create a power balance (e.g., unexpected events)/ Playing their own game</td>
</tr>
</tbody>
</table>
Pandemic- Theatre Edition: Imagining a world balanced through science and art

The analysis of the design practices of the other group of focus, i.e., Pandemic Theatre Edition, is discussed in this section. Similar to the analysis approach for the previous group, this section elaborates on the identified critical emergent episodes in their game redesign, which would represent how the space of their group design evolved. A summary of the critical episodes and the elements of divergence and convergence of ideas and the supporting settings is provided in Table 8.

Developing the game theme and backstory. The group Pandemic Theatre Edition initially thought of creating a game with a similar theme of eradicating widespread diseases, similar to Pandemic, but through different mechanisms. They considered adding theatres instead of research stations to use an art form in developing their game story. After a few sessions of playing the original game, the teacher asked students to discuss their design ideas in their groups again to specify their main ideas and the math and science topics they might want to use. As the students mentioned in the interview session, this encouraged all the group members to put their ideas together, revisit their initial decisions, and come up with a new theme. They chose to develop a new backstory, different from Pandemic, about making a balance in the world in terms of people’s happiness, which depended on the climate conditions, by moving people across the world. Their game backstory included hot and cold places impacted by climate change and areas with sad and “overly happy” people who would destroy the environment. This theme was also connected to their decision of using the heat and temperature topic at the time. They decided to have research stations, which could help people in hot and cold areas, and theaters, which could balance people’s mood. It was notable how they separated the regions impacted by climate change and the regions that worsen the environmental conditions and how they considered the role of both science and art in creating a balanced world.

Using Pandemic’s components to create a form for their game and enact its story. In the following sessions, the group focused on how to enact their own game backstory. They started evaluating how they could use or modify Pandemic’s components in their own game. Their ideas converged into using the cubes (representing diseases in the original game) as symbols of moving populations among different cities. They used the Pandemic’s board to
discuss their ideas on how to use a map in their game and move people between different areas (Figure 41-a). After considering possible geographical scopes for their game, they decided to use the map of the whole world and to not limit their scope.

They also modified the infection deck in *Pandemic*, which added cubes to the board, to tell players how to move people between areas in their game. In moving people between different areas to make a balance, they used the concept of percentages. Each player needed to calculate a specific percentage of the cities’ total population to determine the number of people to be moved. They also talked about how their game represented the concept of negative numbers as players needed to move people between the cities with opposite conditions: “Our game had already been using negative numbers in a way because you move … (people from) a yellow city to a black city to cure it because these two cancel each other” (Ethan). Their developing game theme also allowed them to connect their game more to the science topics of interactions and ecosystem, using them in a symbolic way. For example, they created a “world climate health meter” for the environmental condition. As the condition gets worse, moving between cities becomes more difficult: “when the world health meter gets to like a certain point, … you can no longer fly unless it’s a shuttle flight at the research stations” (Ethan).

**Figure 41**

(a) *Using the Pandemic game board to discuss how to use the map and move the population between the cities,* (b) *discussing players’ roles*

The group also decided to have different roles for players for creating the intended balance in the world (Figure 41-b). They, for instance, discussed how “a director could move people on their turn” and “the actress can cure depressed people,” while a group member suggested the role of an environmentalist who can “discard a card in research stations or theatre … (and) move the climate health meter up.” Before designing their role cards (Figure
42), they also had extensive discussions about these roles’ gender and power. The below conversation reflects part of these discussions:

Ann: Why did we choose the stage people to be a girl?
Ethan: I think it should be anonymous! Until we do the drawing. It could be an actress or an actor.
Alma: The scientist should be a girl.
Ethan: Yes, the scientist and the actress should be a girl.
Ann: Yes, and the director can be a boy.
Alma: No, the director should be a girl. My feminist part tells this. The director is a girl!
Ethan: Okay, and the builder is a boy.
Ann: No! Girls can be builders too. ...
Alma: And the president.
Ethan: A president?
Alma: Yes, the president can save the hot people…. The president is a girl.
Ethan: Yeah, because Donald Trump didn’t win the election in this world.

This conversation also led to an emergent discussion on the US electoral college process referring to the Clinton-Trump battle in the 2016 presidential elections. Such interactions suggest that the human aspect of their game theme provided the space for the group members to relate more with the task. Their conversation around the characters’ genders and the emergent political discussion implied how they were critically engaged in challenging the perceived boundaries around gender roles. This is an experience of “transitional othering” (Sengupta et al., 2021), because these group discussions illustrate how, in creating their imagined world, symbolic representations of human actors became a venue for learners to express their perspectives as if they saw themselves in relation to others in this modeled world (Sengupta et al., 2021).

Figure 42
Final role cards
Engaging with complexities in materializing their imagined world. The group’s decision on using the whole world as their game scope was a significant self-imposed constraint that needed them to specify “too hot” and “too cold” areas in the world and the overall “happiness” of people living in different cities and countries. In other words, creating the actual game elements needed them to explore deeper their idea of imbalances in their game world and the possibility of categorizing the countries based on opposing conditions. This encountered complexity encouraged the group members to exchange their various viewpoints. This is exemplified in the following conversation, started after they recognized they have categorized people in California as “sad” people:

Ema: Why? It’s so nice out there. There’s Disneyland there!
Ethan: Yeah! No, the happy people are in California ((pointing to the map to show it)). Los Angeles is an “is an over happy” city.
Ethan: Russia is sad.
Jacob (from another group): Russia is not that sad.
Ethan: It is sad in our game … Although if you say Russia is sad out of nowhere then you are kind of hatist.

The group also discussed a possible destructive human impact on the environment in the areas where people are “overly happy” because they would not care enough about the impact of their actions on the environment. The decision of having a broad geographical scope for their game did not seem to be significant at the time. It, however, became decisive when interacted with the goal of designing a game with multiple interconnected elements. The group members engaged with complex issues that challenged their simplistic assumptions (e.g., with regards to “sadness” or “happiness” of different regions), and with one another’s perspectives. Ethan’s last utterance in the above conversation presents a dilemmatic situation for him: although he implied that they would need to make simplifying decisions in modeling their game story, he challenged groundless assumptions. The group’s emergent discussions also showcased how addressing a seemingly scientific issue, i.e., climate change in their game, entails attending to social and political factors. This of course signifies the complexity of the problem the group was engaged with in the context of designing a game system.

Envisioning and moving towards further developments in their game mechanics. Developing their board game (Figure 43), the group thought of other design possibilities that
could facilitate moving between cities and create “a new way for interaction” (Ethan, reflection day). Although they could not use all these components in their final game, it was notable how their design process enabled them to expand their view of what would be possible in terms of game dynamics (and the supporting mechanics) and their use of learning topics.

**Figure 43**

*Pandemic Theatre Edition game board*

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**Designing immigration cards: Adding chaos and an element of luck.** One of these design ideas was adding “immigration cards” to the game. Immigration cards would specify selected cities for players to move between. What the cards tell players to do might not be completely in line with what players would need in terms of moving people on the board and could add an element of “randomness” and “chaos” as “things would be moving across the board” (Ethan), as they explained through the interview:

> It would be more fun if we had the immigration cards, because I think people like an element of randomness in games… Every turn you would be getting more immigration cards and things would be moving all over the place. ... So, maybe you’re going to get the one ((moving people)) in Sao Paulo then suddenly it’s moved to London ((based on what the immigration cards would tell)). ... And you go to get the other one in London, but you can’t ... because they move to Moscow and Riad. So, it would add a bit of chaos because things would be moving across the board. (Ethan, Interview session)

Ethan also explained how he was calculating the number of cards required for moving people based on the number of cities and possible destinations, and how he used the software
Component Studio, recommended by their teacher, to make the cards. This endeavor indicated how their system of moving on the map was totally different from the original game, *Pandemic*, and from other groups’ games. They started by evaluating the mechanics of *Pandemic* and, as they went on, they explored the possibilities of transforming their initial design to fit their complex backstory and make their game playable and more meaningful.

From another point of view, the engagement with the possible dynamics of immigrating to other world regions could invoke various other consideration, such as the economic and affective nature of the experiences of migration. At this stage of their design path, however, the group focused more on mathematical aspects of modeling migration in their game and making it more meaningful through considering how randomness could interfere the decision making process in moving people among different regions.

**Using bisections in connecting the cities.** Explaining the math involved in their game and further design modifications, they also talked about having “bisections” between cities, i.e., being able to move to cities halfway in the route to where the immigrations cards point to. This could provide some flexibility in using the immigration cards and hence moving on the board. The following conversation on the interview day highlights their idea of using bisections on their map.

Ethan: The math involved... you would use a bisect marker on the city you did not want any cubes moving to and you were kind of like to the place halfway between each colour and that city.

The researcher: So, why is that important?

Ethan: Because that’s what the bisection is cutting something in half.

The researcher: No, I mean why is that important in your game?

Ethan: It was important because the immigration cards, some of them were useless. like moving something from Sao Paulo to London (showing on the original board)). And some of them were more helpful like moving something from San Diego to Khartoum, because it’s closer to the black here. And then some are annoying for you like moving like something from San Francisco to Buenos Aires. So, with these bisect markers you could make sure the useless cities that are far from any other color would be blocked out easily and you can kind of like bend the immigration cards to your will.

**Using more science.** In their interview, they mentioned how they used interactions and ecosystems through their “world health meter” marker on their board: as the environmental
conditions, represented by this marker, get worse in the world, going forward would be more challenging for players. However, as Ema (one of the group members) reflected, a deeper connection to science was missing in their game. They aimed to use the heat and temperature topic, but it became limited to specifying hot and cold regions. Although it could be a good start, they envisioned possibilities of better connections between their game system and the learning topic.

Table 8

*Pandemic, Theatre Edition - Critical Episodes of group design*

<table>
<thead>
<tr>
<th>Episode</th>
<th>Divergence Elements</th>
<th>Supporting Interactions</th>
<th>Convergence Elements</th>
<th>Supporting Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing the game theme and backstory: Imagining a world balanced through science and art</td>
<td>Exploring how to incorporate an art form/brainstorming on how to use the learning topics</td>
<td>Working on an idea sheet/Group discussions on the session allocated to coming up with game theme and goal</td>
<td>More explicitly connecting their game theme to the learning topics (heat and temperature, and negative numbers)/clarifying what they mean by balancing the world</td>
<td>Discussing ideas with the teacher/Group conversations on the imbalances caused by climate change and what making a balance means in their game</td>
</tr>
<tr>
<td>Using <em>Pandemic</em>'s components to give a form to their game and enact its story</td>
<td>Evaluating the geographical scope of their game and how to move on the board/Exploring the roles their game would need and their powers/Exploring how to use science and math topics in their game</td>
<td>Group discussion/Using and evaluating <em>Pandemic</em>'s components (board, cubes, etc.) when discussing design ideas/Taking notes on their game components and rules throughout the discussions</td>
<td>Deciding on the geographical scope of their game and the rules for moving on the board/Creating role cards/Using the topics of percentages and ecosystems and interactions in their game/Looking for the cities’ population and making city cards</td>
<td>Starting on their rule-book/Group discussions</td>
</tr>
<tr>
<td>Engaging with complexities in materializing their imagined world</td>
<td>Discussing how to determine hot and cold areas and the overall “happiness” of people living in different cities and countries/Discussing the human impacts on the environment</td>
<td>Group discussions/Getting feedback from other groups’ members</td>
<td>Designing their board/Locating regions with specific characteristics</td>
<td>Creating a rule sheet for their game/Using the <em>Pandemic</em> game board to create their own board</td>
</tr>
</tbody>
</table>
Design practices are intrinsically transforming and open-ended and have the potential to support learning. This study structured the design project as creating a board game, based on the potentials of this approach, observed in previous projects (Bastani & Kim, 2020; Kim & Bastani, 2017; Kim et al., 2021). Board games can be connected to or embody disciplinary content knowledge, are accessible (compared to digital games), and have physical components, which could support learners’ communication and idea development. This project was also structured as game redesign (the board game Pandemic was selected based on its features and connections to learning topics) to limit the vast design possibilities of creating a board game from scratch and help student groups develop shared understandings and expectations of their design practices. These structured design constraints at the starting point aimed to support students to develop shared communication channels (Davis & Sumara, 2006). The groups of focus in this chapter used the languages and components of the original game and had common goals in developing new themes, which supported the interaction of their ideas. On the other hand, the open-endedness of the game design task was expected to open the space for groups’ control over their collaborative work and use of learning topics (Davis et al., 2015; Kim & Reeves, 2007).

The analysis of the identified critical events showed that the game redesign approach enabled students’ collective decision making, through which they explored novel paths of design and integrating learning topics: i.e., they expanded their design space. Their interim design decisions acted as dynamic frames that not only structured their work but also became tools for this exploration. Learners’ opportunities of using science and math topics emerged and expanded throughout the project. This was specifically intertwined with learners seeing more possibilities to develop their game backstory and implement their ideas to create a working system. It was also notable how learners’ understanding of the original game’s (Pandemic) rules and its components mediated their discussions on design possibilities and getting deeper in how to use
learning topics in creating a complex system that scientifically and mathematically makes sense.

Further analysis could attend to different group dynamics in evaluating decision making processes and the evolution of learners’ design space, i.e., their consideration of alternative viewpoints, reinterpretation of problems and exploration of design possibilities.
References


Bastani, R., & Kim, B. (2020). Learners’ emergent designs for play: Game design as mathematical modeling practices. In M. Gresalfi & I. S. Horn (Eds.), *The Interdisciplinarity of the Learning Sciences* (pp. 1445–1452).


Chapter 6: Discussion

In the two phases of my doctoral study, I tried to make sense of how learners’ ideas and practices unfold and evolve. I attended to the communications that helped peers or groups come to shared understandings of problems at hand and form shared purposes and coherence. The students’ conceptions of problems also supported how they made others’ perspectives meaningful to themselves (Miyake & Kirschner, 2014) and built on one another's ideas. Approaching the challenge of design for learning from a complexity perspective and my past experiences with learning design projects provided a conceptual structure for me as the researcher that helped me make intentional choices in my design for learning and get feedback from them. On the other hand, I tried to be attentive to emergent dynamics in groups’ design projects and the supporting settings to develop my understanding of how their practices evolved. In this chapter, I further discuss some considerations which emerged across the two phases of this study.

**Learners’ engagement with learning topics and the adaptive role of teachers**

One important aspect of this project was engaging learners with disciplinary knowledge in the context of relevant complex problems. The teachers’ overall approaches, informed by the schools’ and classrooms’ culture and context, and their roles in supporting students’ design projects and engagement with learning topics were significant in shaping the projects’ processes and the learning possibilities that emerged for the students.

As elaborated in chapter 4, in the *Inversé* project with grade-3 and -4 students, I observed how the teacher regularly sat with each group to make sense of their ideas and designs and build on those to engage them more deeply with mathematical concepts and the use of them in creating their games. She introduced the project with some structures (mainly in terms of project stages) to the students but adapted the goals according to the emergent learning possibilities based on students’ unfolding ideas and practices or their challenges with progressing in their designs. Working with grade-3 and -4 students, the teacher had a focus on supporting students’ regular reflections on their work, through discussing their design ideas and use of mathematical constructs and playtesting their games. They also had a class gathering at the end of each session, facilitated by the teacher, so that the groups could share their new ideas and challenges and get feedback from others to improve their games.
In the *Pandemic* redesign project, the grade-7 students could choose from a range of mathematics and science topics based on the game system they aimed to design. In addition, the selected board game to be redesigned, i.e., *Pandemic*, was a complex thematic game with multiple interconnected elements. This could open the space for various ways to approach the redesign of this game for students. The math teacher (the research partner teacher) introduced the math topics that could be used in creating the game to the class, mainly in the initial sessions. He also invited the science teacher to come to the class to have a discussion with the groups about their design ideas. The teacher’s approach was to support the groups’ idea development and help them narrow their ideas down, specifically at the primary stages of the project, and to encourage learners’ collaboration as needed. He had an emphasis on how classroom design projects could be very good contexts for students to improve their communication skills and practice the kind of collaboration that might be out of their comfort zone: “it’s one of my values that you come out of … (this art immersion school) with the ability to work with a variety of people because you don't always get to choose who you work with” (the teacher, interview session). He also aimed to open the space for learners to experience failure and its role in the design process: “It’s okay to fail here and also just above (that) ... it’s about seeking out failure. A designer is constantly seeking failure because you have to find out where it falls down, whether it’s your explanation, whether it’s your artwork, whether it’s the narrative, (or) the engagement that has to be done more quickly. So, the sooner you get to that point, the sooner your game will evolve to become better.”

The school and the teacher’s approach was particularly engaging students with disciplinary knowledge not in isolation but in the context of meaningful interdisciplinary problems. Considering how redesigning *Pandemic* was an interdisciplinary project, he reflected that more sustained and explicit conversations about the math and science topics used in the students’ designs could have deepen their engagement with these learning topics and help them meet the curricular goals better. On the other hand, he reflected on the emergent opportunities for students to also explore the geographical and historical aspects of their game themes and use them in creating their game elements.

It was notable that in both studies the teachers’ approach and the project structure led the teachers to be part of the process the groups had initiated based on their interests and goals in different stages of their design. The teachers had an adaptive role, intervening as they saw the
need and building on students’ ideas and interpretations of the current situation to open up further possibilities for understanding and action (Davis et al., 2015).

Heterogeneity in learners’ voices and multiplicity of perspectives: Group dynamics and individual contributions underlying ideational emergence

The analyses in this dissertation were mainly at an ideational level, addressing the supporting role of the game redesign setting and structures. However, exploring the processes of divergence and convergence of ideas indicated the role of underlying elements of group dynamics in these processes. Examining the group interactions that triggered the emergence of new ideas and meanings could shed light on the matter of heterogeneity in learners’ voices and how multivocality was enabled in learners’ groups by undertaking the board game redesign approach. The construct of voice points to how a word becomes an utterance. As such, it is not a property of an individual, but results from the “social horizon” of a word: “a voice is an act of coming together, in the forms of hearing, speaking, and co-opting of a multitude of voices” (Sengupta et al., 2021; p. 24, Bakhtin, 1986). This also means that “a” voice emerges through a synthesis of multiple voices, that also reflects our varied cultural histories.

Scholars in learning sciences have argued for the importance of students’ heterogeneous experiences and resources in supporting collective learning:

The learning of all students is limited when heterogeneity is ignored or goes unrecognized in the classroom. If learning fundamentally involves the negotiation of meanings across culturally saturated boundaries of practice, including those of academic disciplines, it becomes circumscribed when the space of possible meanings is restricted. (Rosebery et al., 2010, p. 326)

Heterogeneity points to the multiplicity of meanings of a single word, and also indicates that a word to communicate and convey a message is always only half ours, i.e., it indicates the plurality of voices that make a single voice (Sengupta et al, 2021; Todorov, 1984). As indicated in the Rosebery et al.’s (2010) excerpt above, heterogeneity is also conducive to learning. The expression of multiple points of view could enable the negotiation of various perspectives and conceptualizations of issues at hand. An “interplay between perspectives” could help learners “see more” (Sengupta et al, 2021; p. 41), reimagine possibilities and eventually develop a
different coherent perspective on interpreting issues and addressing them.

Scholars have emphasized the structures and activities that could support learners’ voices and the interaction of multiple points of view within learners’ groups (Sengupta et al., 2021; Takeuchi et al., 2020; Zawojewski et al., 2003). Sengupta et al. (2021) particularly point to how the learning settings need to create a space for learners to relate to the issues (e.g., urban migration and racial segregation) in ways that help learners locate themselves in the context of such issues, while enabling them to maintain a distance from them to be able to discuss these issues without seeing them as only personal matters. In the second phase of this research, this was exemplified in the students exchanging their perspectives on how to determine the gender of their game characters and their discussion on politics. The students expressed their critical points of view and challenged the perceived boundaries around gender roles. Symbolic representations of human actors in their game world became a venue for learners to express their perspectives as if they saw themselves in relation to others in this modeled world.

Heterogeneity in classrooms could emerge from various sources and histories that shape learners’ diverse lived experiences and their ways of doing, knowing and being (Kim et al., 2015). Learners’ various kinds of relationships with their peers, subject matters, and classroom authorities stem from their different backgrounds and experiences and sociocultural expectations in classrooms and their other realms of life. The assumption that such diversity exists in any social grouping (Davis & Sumara, 2006) and that the engagement of any individual student in the learning process matter, and viewing diversity as fundamental to learning (Rosebery et al., 2010; Sengupta et al., 2021), make the special attention to the settings that support and build on heterogeneity in design for learning both valuable and necessary.

Further studies can highlight how board game redesign approaches as practices of system modeling could create different control mechanisms in the classroom, shifting it away from the status quo of control being exerted from classroom authorities, the text or peers. They can also expand on further structures that can facilitate such shifts of control through board game redesign approaches. This line of future research could also elaborate the potentials of collaborative board game redesign for disciplinary learning, in allowing for complexity-informed conditions, importantly enabling diversity and decentralized control in the classroom and within student groups (Davis & Sumara, 2006).
In the Inversé redesign project, the classroom was highly diverse in terms of students’ backgrounds, their academic records, and their past education contexts (e.g., attending public school or home-school). Reflecting on this project, the teacher specifically mentioned the unexpected patterns in students’ engagement with the learning tasks. She pointed to the students in the math class that did not see themselves as “math person(s)” despite their “good math sense” and some other students who had challenge with focusing or communicating their ideas. She emphasized the cycles of design and getting feedback and specifically groups sharing their work with the rest of the class. This process helped the students make sense of their design path and the designed game rules. It also encouraged them to take the lead in certain stages of the project and in explaining their design to others using the multiple modes available in this project (e.g., using and creating the game components and playtesting their game). Drawing on his experience with Chinese cultural games, a newly arrived-immigrant student (an English language learner) could enrich his group’s mathematical practices through their game redesign project. In another work (Kim, Bastani & Takeuchi, 2021), we have elaborated on how his cultural and linguistic resources made the task relevant to him and helped him participate fully in the project. His perspectives also opened the space for his group to explore new design possibilities while deepening their understanding of how the mathematical constructs could be used in creating play situations.

The students who participated in the Pandemic project were less diverse in terms of their backgrounds. However, the differences in students’ skills (e.g., art and design skills), their approach to the group projects, their experience with board games, and their relationship with learning topics were notable and created various group dynamics. The teacher reflected on how the interest in playing board games engaged some less expressive students in the project (e.g., in understanding and explaining the rules). Redesigning a thematic board game also engaged the group members in researching and developing the different aspects of their game stories. As mentioned above, the complexity of some of the game themes enabled the group members to express their critical views on social and political issues connected to their game, seeing themselves in relation to others in the modeled world of their game. There were, however, instances of univocality in certain stages of design in some of the groups and occasions of group conflicts that hindered the groups’ progress in their designs. The teacher’s intervention in those stances and explicitly asking the groups to reflect on their own and one another’s ways of
contribution supported a more balanced dynamic in groups. At the later stages of the project, within-group playtestings, the goal of improving their games and the anticipation of sharing their work with other students entailed an active participation of all the group members. This took place in the forms of game play and executing the rules, therefore understanding the different aspects of their game, and their exploration of areas of improvement. This helped the students express their ideas and attend to one another’s viewpoints.

The control mechanisms stemming from univocality could suppress higher conceptual possibilities that could arise from the exchange of various perspectives. However, it is important to note that even in the instances of an individual member leading the group work, the past interactions of multiple perspectives, decisions and expectations, shaped at the group and class levels, were present in the leading individual’s voice. I captured occasions of individual students thinking aloud about design possibilities that reflected the multiplicity of voices arose through the social and material interactions in this game redesign project. These observations were illustrative of how “a single voice” is not a standalone voice owned by an individual member (Sengupta et al., 2021).

Further analysis on the group interactions and exchange of perspectives could explore deeper how the game redesign approach could challenge possible control mechanisms coming from peers, classroom authorities, and subject matters, and what further structures could help the board game redesign approach move towards this goal. It could specifically attend to how encouraging dialogue between diverse points of view, stemming from learners’ multiple perspectives and their interactions with tools and materials, could provide higher conceptual and practical possibilities.

“Muddling through as a deliberate design strategy”: Supporting both continuous exploration and convergence of diverse ideas into shareable artifacts

The findings in the previous chapters showed how the game redesign task encouraged learners to imagine multiple models and scenarios. I observed how developing ideas on the game’s backstory and game elements engaged learners with discussing various aspects of the system they aimed to model through their game design. This not only enriched their conception of the thematic problems and design possibilities but also engaged different group members with varying interests and perspectives to be fully engaged in the design process (Baradaran Rahimi &
Kim, 2019). On the other hand, I observed how some of the groups’ continuous exploration of ideas and willingness for coming up with a comprehensive backstory, differed their implementation and testing of their designs until the end of the project. This particularly made having a playable game challenging for some of the groups. This issue raised the question of how we could both encourage learners’ exploration of ideas and support converging their diverse ideas into sharable artifacts in a more balanced way.

Norman and Stappers (2015) specifically used the term muddling through (Lindblom, 1959) as a principle of design when facing complex issues. This concept refers to focusing on small incremental steps rather than tackling the whole design problem at once. It involves limiting the focus on a particular layer of design, i.e., identifying the problems at hand and exploring sufficient rather than optimal solutions, implementing them and reflecting on them. In the future iterations, designers could explore new design possibilities based on how their design interacted with the real world. They could address the new aspects they need to attend to or the new conditions they need to adapt to. This also opens the space for using the relevant specialized knowledge in addressing the problems more systematically. In other words, in a learning environment, the structure should support early sharable drafts for receiving feedback and adapting the goals. These preliminary prototypes would serve as interim accomplishments for learners and tools to think with and explore more ideas.

The design process of some of the groups in the Pandemic redesign project presented how this approach could be helpful. As the teacher reflected in our discussion on the groups’ different design processes, the starting focus of the Reverse Pandemic group on using the original game and reversing its theme and the Mauritius Pandemic group on having a limited geographic and historical scope, at the beginning of the project acted as an “isolating layer” that the groups could start with and gradually build upon. He emphasized the role of “the strong focus of the beginning” and how “that is the art of making the complex, simple” in design and, in a sense, “the hard thing about creativity”. As he asserted, the relatively narrow focus at the beginning would make the design process feasible, as designers wouldn’t have to deal with too many elements, while such focus becomes a building block for further explorations. He also signified “trying to create a simple thing they can do together … (which) gives them success in the beginning, … (the group) would get an identity of ‘we are a successful capable group.’” In the case of game design, learners’ groups need to gradually come up with a common narrative of
themselves as a group and their game, i.e., their game story: “narrative is a strong medium” through which they can “assemble the information and recall it” as they add layers to their design and make it more complex. He pointed to the significance of these observation from an instructional design perspective, and how this approach could be more explicitly used in redesigning this project for his future classes (the teacher, interview session after the Pandemic redesign project).

In addition, clear deadlines have also been considered as the kind of constraints that could be conducive to the convergence of ideas in design projects and moving the creative process along (Amabile et al., 2018; Norman, 2013).

Attending to such structural support for both exploration of diverse ideas and the convergence of ideas in groups speaks closely to the notion of enabling constraints, i.e., creating the conditions for both vibrancy and coherence in learning systems. On the other hand, it underscores how creating these conditions requires a careful evaluation of the local context and the various processes and patterns that unfold in different learning projects. As not all the possible aspects of learning activities could be predicted before implementing them, this endeavour should be pursued taking an adaptive approach to design for learning, i.e., attending to emergent patterns of idea development and group and class dynamics to adapt the structures in the learning settings (Barab & Squire, 2004).

**Revisiting the notion of enabling constraints: Structures that allow for randomness and self-imposed frames**

The analysis of data from the Inversé redesign project on learners’ evolving designs and the variations in their use of learning topics and their artifacts (Chapter 4) highlighted the role of groups’ co-constructed constraints on their work. Learners’ evolving interpretations of problems and possible solutions through the cycles of design and playtest were intertwined with the emergence of co-constructed commonalities, as developing constraints that stimulated specialized paths of using mathematics in groups. The groups iteratively set new goals based on the unique game features of their interest and their ways of using mathematics to make their games playable and meaningful (e.g., making them balanced and embedding both strategy and chance elements).
In analyzing data from the *Pandemic* redesign project (Chapter 5), I elaborated on the evolution of groups’ design practices, more specifically attending to the divergence and convergence of learners’ ideas and the settings that supported them. Throughout the identified episodes, students’ design goals and conceptions of possible design solutions, thus their design space, evolved (Biskjaer & Halskov, 2014; Norman, 2013). An example of the primary analysis of these transformations and the constraints involved was presented in Table 6 in Chapter 5. Here, I further discuss how the structured constraints involved in the board game redesign project and the emergent constraints mainly stemmed from the groups’ interests and decisions enabled learners to expand their use of math and science topics, shape and adapt to new collective goals and progress in their design project. This also highlights a connection and continuity between structured constraints and learners’ self-imposed constraints emerging through the process (Figure 44).

**Figure 44**

*Structured and self-imposed constraints in an evolving design*

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*Structured constraints and tentative boundaries: Laying the foundations for an open-ended task*

The stages of this project aimed to provide a structure within which student groups could develop common languages and collective purpose that became the underpinnings of group interactivity and idea exchange (Davis & Sumara, 2006). The project structure, mainly starting
from a selected common game and the groups’ goal of redesigning it, acted as constraints for the broad range of possible design approaches the groups could take at the starting point. In the following, I discuss these structured constraints and how they could enable the groups’ focus and progress in their designs.

**Playing the original game to decode and destruct what is at hand.** The groups started with playing *Pandemic*. It was notable how as they engaged with their designs, they needed to further decode this game’s system. This, in turn, supported their idea development and decision making as they progressed in their project. The shared understanding of what is at hand and the agency to restructure it could stimulate their imagining of possibilities within the frame of the game redesign task and their idea exchange. As the teacher put it, there is a mutual relationship between creation and destruction of what already exists, which could be supported in this game redesign project.

**Using the original game’s components as tools for communicating and materializing ideas.** The group discussions showed the original game’s components acted as tools for students to interact and come up with the elements that would enact their game story. Importantly, this process could support the groups’ focus on the core elements of their own design. The groups had the opportunity of modifying the existing components, i.e., using what already existed in a way that would fit their game (e.g., *Reverse Pandemic*’s use of a similar map as the original game), while creating what they needed for their unique game (e.g., changing the cities’ grouping to have a 6-player game). This signifies an enabling aspect of redesign and the constraints involved in it, compared to designing from scratch where the broad scope might limit the groups’ possibilities of developing focus and translating their ideas into sharable artifacts (Kim & Bastani, 2017).

**Attending to project goals and deadlines: Staying within the boundaries of the project.** The project had goals and limitations which set overall boundaries for the groups’ work (Davis et al., 2015). They mainly included incorporating math and science topics in their redesigned game, the project deadline, and having a shareable game to be played with other groups and students. This overall framework supported students’ shared understanding of expectations (Davis & Sumara, 2006), the convergence of ideas in groups, and the groups’ making sense of the goals and systems of other redesigned games. On the other hand, there were
variations in how the groups approached these constraints in different stages of their design, which led to unique design trajectories for them. For example, having a balanced game by the deadline encouraged the group *Reverse Pandemic* to have early game drafts, which they could test and get feedback from. This is while the group *Pandemic-Theatre edition* focused more on developing their game backstory making it more complex and meaningful, but less on playtesting before the deadline. I observed the important role of groups’ interim choices and decisions as self-imposed constraints in shaping their emergent design process, which I discuss next.

**A continuity between what is structured and what emerges through learners’ participation**

The open-ended process of design entails iterative goal setting. Designers need to revisit their conceptions of problems and alternative solutions, as ideas interact and they get feedback from their prototypes (Norman, 2013; Sternberg & Kaufman, 2010). This could create the setting for learners to adopt intentions in approaching the problems and in incorporating learning topics (Barab & Roth, 2006; Kim et al., 2015). The critical episodes of the groups’ design practices showed how as learners participated in the design project, structured as redesigning a particular board game, they engaged in intentional interactions with their peers, teachers and learning topics, using design materials and their developing artifacts. It showcased an interconnection and continuity between structured constraints and learners’ self-imposed constraints emerging through the process.

**Learners expanding and deepening the use of learning topics building on their design decisions.** The groups’ interim design decisions were self-imposed constraints, which acted as dynamic frames that not only structured their work but also became tools for idea development (Biskjaer & Halskov, 2014). Students’ use of science and math topics emerged and expanded throughout the project. This was specifically intertwined with learners’ seeing more possibilities to expand their game backstory and implement their ideas to create a working system. As an example, the group *Reverse Pandemic* incorporated numbers, percentages and probabilities as they went through materializing their ideas, following their intention of having a playable and balanced game. Their exploration of possible mechanisms that could enact their game story triggered adopting a scientific approach through taking the perspective of bacteria and viruses. This helped them make a better sense of the emergent process of disease spread at
the global scale. Learners’ understanding of the original game’s rules, which developed due to its contribution to their own game design, helped them get deeper into the possibilities of using mathematics in creating a complex system.

**Engaging with complexities in developing their imagined backstory and transforming it into a playable game.** The game redesign project was a context for modeling an imagined world developed by students. The groups iteratively developed the backstory of their interest to make it more meaningful. This became a self-imposed frame that triggered their design trajectory. The sophistication of *Pandemic-Theatre Edition*’s backstory, for example, encouraged divergent ideas through the design process. This included both ideas for adding details to their game story and goal, making it more meaningful, and the design ideas that attended to possible game dynamics and mechanics to enact their story. This led the groups to engage with emergent discussions on the multiple aspects of their game theme and make a better sense of the complexities involved as they pursued creating their modeled world through different signs and symbols.

*Further reflective thoughts on enabling constraints*

The learning design in this project supported various ways of approaching the learning topics. It opened the space for random encounters that could evoke imagining new possibilities and creative solutions, making the groups’ engagement with the tasks vibrant (Davis & Sumara, 2006). That is, learners were exposed to a range of ideas and possibilities as they revisited their designs, expanded their conceptions of problems and opportunities of using learning topics, and interacted with the teacher, their peers, and game-design materials.

The observations of groups’ transforming practices point to how the structured constraints were enabling in the sense that they could support self-imposed constraints, i.e., learners’ ideas, decisions and interests, as learners participated within the structure. The designed settings could open the space for learners to be intentional in engaging with the tasks, incorporate their interests, anticipate the consequences of each step, and shape their evolving understanding and actions.

Iteratively coming back to my understanding of the notion of enabling constraints through my doctoral research, I found that attending to enabling constraints is not as a matter of optimization between the imposed structure and the required openness for the expression of
diverse ideas and interests, as if they are independent concepts. It is more about a continuous interaction between these two aspects rather than trying to create an optimal state. That is how the structure could lead to an openness for learners to become participants in learning activities, attend to their own interests and choices, and evolve with them.
References


Chapter 7: Conclusion

This research followed a conception of learning as a complex phenomenon and explored the possible ways of supporting it. A design-based research was conducted to explore the potentials of a board game redesign approach in providing the settings for complexity-informed design conditions. This learning design’s goals involved stimulating new possibilities of collective understanding and action for learners, while supporting their pursuing their ideas and interests, in an interdisciplinary project.

The critical review of the literature on complexity views in the learning sciences elaborated on how these perspectives could conceptually frame learning designs. Importantly, the literature on using enabling constraints (Davis & Sumara, 2006) has been prominent in introducing the pragmatic potential of using complexity views in educational projects. There was, however, a lack of design studies examining the proposed design conditions within the enabling constraints debate.

The notion of enabling constraints (Davis & Sumara, 2006), informed the two phases of this study. The first phase involved using the framework of enabling constraints to analyze commonalities and variations in the students’ collaborative redesign of the board game Inversé in an elementary mathematics classroom. This analysis highlighted the importance of structured constraints at the starting point, mainly students’ playing the same game and aiming to redesign it, in supporting a common language. It also showed how the groups’ progress and the unique paths of transforming their designs and use of learning topics were essentially intertwined with the emergence of co-constructed commonalities, as developing constraints (e.g., making their game balanced and incorporating specific game features). This analysis, therefore, indicated the interconnection of the constraining and enabling aspects of the developed commonalities throughout the process.

The study in the second phase adopted the board game redesign approach from the first phase with more explicit use of complexity-informed conditions in its design for learning. In this phase, grade-7 redesigned the board game Pandemic using math and science topics. Based on the finding in the first phase, I modified the analytic frame using design and creativity research. I used the notions of divergence and convergence of ideas and self-imposed constraints (Biskjaer & Halskov, 2014; Sternberg & Kaufman, 2010) in connection with the notion of enabling
constraints enabled a deeper focus on the processes of the evolution of learners’ practices and understanding. My analysis attended to the divergence and convergence of ideas in students’ groups and the role of structured and self-imposed constraints in supporting this process. The findings indicated how the board game redesign approach provided some structure for students’ collaborative design practices to support the communication within and among the groups, while enabling students to negotiate their interests and choices. In this process, learners could get involved with collective decision-making. This study elaborated on how students’ decisions could act as self-imposed constraints that frame their work and could enable their evolving goals and further exploration of learning topics. This pointed to the possibility of a continuity between the designed structure and learners’ self-imposed constraints that could act as tools for learners’ further exploration of possibilities and transformation of their assumptions and goals.

The following sections highlight the limitations and delimitations of this research. I also address the possible future research directions that could stem from this doctoral study.

**Limitations and delimitations of the study**

This dissertation has a number of limitations. The contexts of the two studies addressed in this dissertation were different from multiple aspects. Importantly, in terms of students’ age, the schools’ culture and approach (the first phase was conducted in a CBE elementary school and the second phase was conducted in an Art Immersion charter school). Although I tried to provide some contextual information in reporting the data and discussing the teachers’ approaches in supporting the students’ collaborative work, further analysis could enrich understanding the connections among the contextual elements and the emergent learning possibilities.

The projects addressed in both phases were also conducted in the same city in Alberta, Canada. More inclusive studies in terms of the geographic and cultural contexts with a board game (re)design approach can provide the opportunity for comparative analyses to shed light on how the learning design elements would interact with particular cultural and local factors (e.g., curricular goals, relationships among teachers, students and subject matters, and past experience with board games and design projects).

The second study also used a board game with complex rules to be redesigned. It was expected that this aspect could encourage divergent ideas and interdisciplinary approaches in
learners’ design processes. However, the complexity of the rules made the process challenging in the initial sessions, especially with groups who were not familiar with such cooperative board games. Further analysis can explore how the unfamiliarity of the board game and some of the groups’ prolonged engagement with the mastery of the rules, which differentiated the groups’ starting point, contributed to the differences in the groups’ design and learning processes. On the other hand, further studies using different thematic board games could highlight how the complexity and structure of the board game to be redesigned would contribute to learners’ engagement with the mathematics and science topics of focus.

As for the delimitations, this study was focused more on the coevolution of learners’ ideas and practices and how the structured and self-imposed constraints enabled emergent learning possibilities. Research and analysis on group dynamics could address the process of idea development and transformation of designs in relation to group dynamics. It could include how learners’ relationships with their peers, project structure and subject matters could contribute to their expression and pursuit of their ideas and interests.

The exploration of the schools’ and classrooms’ assessment approaches and processes was out of the scope of this study. These processes, however, could contribute to learners’ engagement and motivations for participating in the projects that are different from the classroom routines. It could also affect how teachers approach the goals of such projects and adapt their responses to emergent learning possibilities, and the needs for structural changes throughout the process.

Future research directions

In the discussion chapter and addressing the limitations of this research in this chapter, I touched upon some potential future directions of research. Importantly, future research could shed light on the role of heterogeneity in learners’ voices and perspective taking in provoking the diversity of ideas in groups and supporting collective practices and understanding (Roseberry et al, 2010; Sengupta et al, 2021). The group dynamics can be further analyzed to uncover how the control mechanisms in the class, specially exerted by peers, classroom authorities and the subject matters can be challenged in the game redesign approach, and what further structures could be helpful to achieve this.
Future research could also explore the potentials of board game redesign in providing complexity-informed conditions for supporting disciplinary and interdisciplinary learning. Importantly, further research could highlight how the choice of the board game to be redesigned could support learners’ common language and expectations and their engagement with the learning topics of focus. It could also attend to the interim interventions in the design process that could support students to move forward with their designs through incremental steps in a reflective manner, while allowing for their intentional engagement with the tasks.
References

