

Mental Models, Meaning, & Games: An Interpretative Phenomenological Analysis of Player
Meaning Making in a Complex STEM Themed Video Game

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2021

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Program Authorized to Offer Degree:

Information School

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Abstract

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This research addressed increasing understanding of how players make meaning during play of a complex STEM game and explores to what extent player mental models of STEM concepts shift as a result of interacting with the game simulation. Game based learning is attracting increased attention and interest as a novel platform for experiential learning, especially during the COVID-19 pandemic. The affordances of real-time interactive simulations in video games are being leveraged to create complex games for learning, designed with components arranged to reflect models of real-world systems in physical, biological, and social sciences. To build these models, designers use the complex multimedia nature of video games to encode and represent information in an array of game components with key attributes and relationships with one another, to provide a system that players can interact with to achieve game goals. Much work

has been done to study outcomes of learning games in terms of post-intervention knowledge assessments, but relatively little has been done to explore the process of player mental model construction and adaptation at the level of specific interactions with components over time. This research aims to expand understanding of how players make meaning during gameplay in the STEM themed game *Oxygen not Included*, specifically through their interaction with game objects and their relationships. Using the approach of interpretative phenomenological analysis, in conjunction with formal analysis of gameplay and continuous think-aloud interview techniques, this work endeavored to collect rich qualitative data on player meaning-making processes during gameplay to address the following research questions: What major themes of interpretation can be identified for youth meaning making of knowledge structures in games for learning? To what extent do player mental models of STEM phenomena that are modeled in game shift during play? What are design implications and recommendations for learning game designers based on these results?

Chapter 1: Introduction and Theoretical Framework

Objective

The purpose of this work is to increase understanding of how game players make meaning of game elements and systems, through interaction with game-based learning environments that model real world phenomena, and to increase knowledge of how players come to understand and interpret these phenomena through play experiences. This work focuses on player interaction with and interpretation of game elements such as components and rules, the systems they compose, the consequences of their interactions with these elements, and their interpretation of these phenomena. It seeks to deepen understanding of the processes that bridge interaction with formal game elements, with how game players build and adapt mental models from these interactions, and how they subsequently make meaning of game systems. To achieve this, a novel approach links a controlled method for understanding game design and form with interpretative phenomenological analysis, a qualitative, inductive approach to understanding how people make meaning from complex phenomena and experiences. The objective is to generate rich descriptive findings on this meaning making process, determine major themes and patterns of interpretation, and use the results to answer the research questions. Findings will be analyzed, novel findings will be highlighted, and results will be compared with existing theory and literature.

This research seeks to answer the following questions:

R1: What major themes of interpretation can be identified for youth meaning making of knowledge structures in games for learning?

R2: To what extent do player mental models of STEM phenomena modeled in game shift during the course of play?

R3: What are design implications and recommendations for learning game designers based on these results?

Relevance of Work

Video games are now a ubiquitous form of media in society, and educators, scholars, and game developers are keen to capitalize on the medium and use the popularity and affordances of games in novel ways to provide people with unique learning experiences. Video games are now a dominant medium in households not just in the United States, but across the world. In 2019, the global video game market generated \$152.1 billion in revenue, exceeding the global film industry (\$136 billion) (Newzoo, 2019), supported by 1.2 billion video game players worldwide (Video Game Stats Database, 2019). This includes a revenue of \$43.4 billion in the United States, with 75% of all households now having at least one video game player. The economic impact of learning game development is also notable, as development and investment in learning games reached an all-time high in 2019, with Metaari Advanced Learning Technology market analysis reporting a record \$2.52 billion invested in learning games that year. (Adkins, 2020)

Educators have long been interested in video games for learning, and developers are interested in new ways to design games for learning and are keen for new insights into effective learning design. This interest builds on a long history of “hit and miss” efforts at creating good learning games. In the 1970’s, game developers began to create games to teach students knowledge and skills. Classic examples include *The Oregon Trail*, *Math Blaster*, and *Mavis Beacon Teaches Typing*. Early discussions of games for learning often focused on the intrinsically motivating aspects of games (Malone, 1981; Hoffman & Nadelson, 2010; Lepper, 1985), and often referred to these games as “edutainment”, the merging of education and entertainment (Hogel, 1996). As computing technology advanced, knowledge of both general game design and game design for learning progressed. By the early 2000’s, the scholarly dialogue surrounding games shifted from a focus on motivational aspects of games, to the growing promise of video games as affording opportunities for more complex and deeper learning. There is also a rich tradition in GBL research of scholars decrying the lack of theories or frameworks for good learning games, “what we learn from the few available studies is far from being comprehensive to provide us with a list of successful design features for good educational games” (Kafai, 2006), and Kiili observed in 2005 that “a model that successfully integrates educational theory and game design aspects does not exist”. (p.13). Many learning games have also been criticized for taking material to be learned, and then

enveloping it in poor game design making the game neither particularly engaging nor effective. In 2001 Brenda Laurel famously used the term “chocolate covered broccoli” to describe this type of game.

Other scholars and practitioners have expressed a need for both additional theoretical and design understanding of learning games, but also practical deployment in contexts such as classrooms (Rice, 2007; Turkay et. al., 2014) and museums (Gammon & Burch, 2008; Hornecker et. al., 2012). Gee (2005) described video game simulations as “fish tanks”, and noted “with today’s capacity to build simulations, there is no excuse for the lack of fish tanks in schools” (p.12) Yet scholar-practitioners studying practical application of games in learning environments have described mismatches between game design, and appropriateness for the constraints of a classroom environment. (Marklund et. al., 2016)

While designers and scholars have improved and expanded effective and engaging design, and some developers are designing for the needs and constraints of particular contexts, there are calls for further work toward understanding aspects of how people learn from games.

Justification of Research

This research seeks to answer the question, **“How do middle school learners make meaning of game systems and components that model real world phenomena through their experiences interacting with them in game-based learning environments?”**

A consistent gap in the field is understanding the cognitive processes that engage interaction with elements at a granular level, and bridge them to a system level. In 2004, Gee wrote “good games help players see and understand how each of the elements in the game fit into the overall system of the game and its genre (type). Players get a feel for the ‘rules of the game’ – that is, what works and what doesn’t, how things go or don’t go in this type of world.” (p.22) It is assumed that as players understand the components and systems in a game, they learn “how things go”, or when real world domains are represented, they learn something about components, systems, and how a domain works. Scholars have called for additional research and understanding into how this process occurs, and what it is like for player-learners.

In 2013, Arena & Schwartz partly problematized this space in a paper on GBL, stating “current models of video game motivation do not connect to the granular level of single design elements”. (p.13)

They describe a lack of understanding on how players understand smaller game elements (components) and the processes they use to understand them as parts of the greater whole of the game. In 2017, Wasserman & Banks (2017) took another step toward understanding game-based learning at this juncture and observed that players find discrete entities easier to identify and externalize than complex relations. They also concluded that players attach conceptual meanings to individual components, a process they call “lamination”, i.e., the material component and the concept it represents are seen simultaneously material and ludic, fused in player descriptions.

This team concluded that one barrier to game-based learning is limited opportunities to test and iterate, and this barrier can be overcome by “providing learners more opportunities to iteratively test their understandings of the relations in the game system”. (p.618) This is a limitation of analog games, which are subject to time constraints that video games are not. One direction for future work they recommend is research that examines “understandings of complex systems when coupled with games or gameful simulations in ways that leverage the phenomenological learning resources identified above, including the lamination of formal game entities”. (p.629) This work expands on these ideas by moving the game model of focus from analog to digital, and substituting the grounded theory used in this work with IPA. IPA is an ideal approach for the novel and complex models formed in modern video games. IPA examines not only what, but more fundamentally how meaning is attached to game elements and develops themes of how players come to understand complex game models in terms of these elements and their relationships.

Research Framing

Fig 2. below represents a visual metaphor for this work. Each of the colored diagrams represent knowledge domain concepts, and each arrow represents a process. In this explanatory metaphor, the first abstract shape on the left represents a given knowledge domain or ontology as it is understood by experts, such as chemistry, physics, and engineering knowledge. In other words, “real world” knowledge and theory.

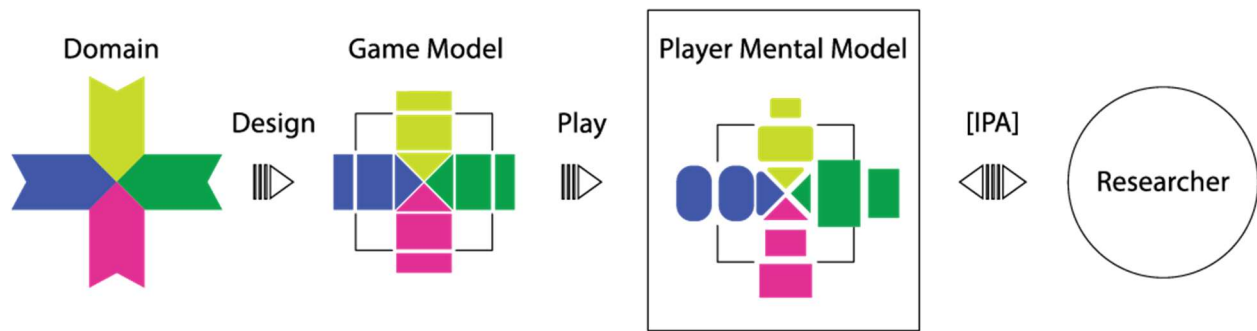


Figure 1. Visual metaphor of key research framing

The domain knowledge is mapped to a game model through a process of design, indicated by the “design” arrow. The design process includes principles of game design, game mechanics, formal components, and game systems that integrate domain concepts. The result of this process is represented as the “game model” diagram, which is the model of the real-world system as built from formal game elements. In this diagram, the domain knowledge has been simplified and some detail has been lost by abstracting it into the game model, which is now composed of discrete game components, rules, and systems. Additionally, the model is integrated with game specific elements such as narrative, characters, and goal structures, represented by the white block it is embedded within.

Next, through game play, represented by the “play” process arrow, players engage with and experience the game model. The player’s mental model (schema) of the domain exists within their own mind, represented by the black box. At the beginning of the play experience, the player brings their existing schema to the game, and via the play process it changes through their experience interacting with the game model. In this diagram, the player’s schema differs from the game model and domain knowledge as best understood by designers, and it changes throughout the play experience. The final diagram is a circle representing the researcher, who is connected to the player via the process of IPA. The IPA process arrow points in both directions, as this is a two-way dialogue between the researcher and player, as the researcher works with the player to understand what meaning the player is making and how they are making it, and what their understanding of the game phenomena is.

It is the crux of the final two diagrams that represents the focus of this research. Using IPA, this research aims to increase understanding of the processes bridging player interaction with game elements and systems, by building themes from critical examples in the data.

Chapter 2: Literature Review

Learning and Meaning Making

This work explores how learning takes place in a game based environment and requires a definition of what learning is and theory on how it occurs. Learning is defined in many ways, and there are many different theories of learning. For purposes of this research, I adopt two overlapping definitions of learning. Kolb (1984) states “learning is the process whereby knowledge is created through the transformation of experience” (p. 38), and Mazer (1986) defines learning as “a process of change that occurs as a result of an individual's experience”. The common elements of these are that learning i) involves cognitive or psychological change or transformation, and ii) such change is a response to novel information or experiences. These definitions each invoke three critical aspects of learning that this research most heavily engages- process, experience, and change.

This research is framed by three nested learning theories that provide key assumptions and framing of the work and help form the specific operational definition of learning used in this project, introduced here, and expanded upon later in the introduction. First, at the highest level this research adopts constructivist learning theory, (Piaget et. al, 1952) which explains that learners have schema, or “mental models” of phenomena, and that these schemas can change with the introduction of novel information or experiences. Second, this work invokes experiential learning theory (ELT) (Kolb, 1974), a narrower learning theory that falls within the constructivist paradigm. Experiential learning theory states that people learn through a cycle beginning with a concrete experience, leading to observation, conceptualization, and experimentation, and eventually back to new experiences. And third, this work adopts the assumptions of game based experiential learning (EGBL), which itself is a specific

conceptualization of Kolb's ELT adapted to the experiences of interacting with the game media formats. EGLBL adopts the core elements of Kolb's experiential learning cycle and integrates design elements of games to describe how games can afford learning experiences.

Based on this theoretical framing, and the definitions of learning previously introduced, this work will use the following operational definition of learning: "a cognitive change or transformation as a response to novel information or experiences". For purposes of this research, the "experience" of focus is interaction with a game-based learning environment, the "novel information" is expressions of the game model as well as consequences of game interactions, and "transformation" is a change in understanding or behavior within the game state, particularly tied to elements of the game. Games are complex media and can provide many opportunities for learning in multiple ways, underscoring the importance of understanding what learning is and how to identify when it is occurring.

"Meaning making" is a term used in parallel or in place of "learning", that this work also adopts as it invokes the concept of interpretation and complements the interpretative phenomenological analysis approach of the study. Meaning making was a concept first proposed by Postman & Weingartner in a chapter titled with the same term in their seminal 1969 work, "Teaching as a Subversive Activity". These scholars preferred "meaning making" to other "metaphors of the mind" used for teaching and learning used in schools, as it stresses a process view of thinking, and focuses on the individuality and uniqueness of the meaning maker in interpreting information. (p.91) Postman & Weingartner were among scholars challenging the once prevalent notion that all learning occurs in the same way, and that there is some finite limit to what can be learned. To Postman & Weingartner, "the meaning maker has no such limitation" (p.91). Meaning making is aligned with constructivist learning theory, in that they both assume that learners construct knowledge and integrate it with their existing schemas. It is also useful within experiential learning theory, as IPA's emphasizes meaning making as it occurs in the mind of a subject based on their experiences. This utility is integrated in the decision to use IPA as a research approach, as IPA emphasizes a process view of learning, entwines learning with meaning making, and centers the subjective perspective of the research participant. This concept will be used in discussions of what learning is taking place.

Constructivism

Constructivism is a theory of cognitive development proposed by the psychologist Jean Piaget and holds that learners construct knowledge and meaning from socialized processes and experiences (Piaget, 1936). Piaget held that knowledge is not gathered or transferred like water in a vessel from teacher to pupil, but rather that knowledge is constructed in the mind of the learner. It is a developmental theory that posits learners have “schemas” or mental models of the world, and as people gain new knowledge, observations, and experiences this mental model of the world adapts to new information through processes such as assimilation (adding new information to an existing schema), and accommodation (changing a schema to deal with new information). It also defines equilibration as a force that drives learning, a tendency to restore a state of balance that exists when new knowledge conflicts with existing knowledge, motivating a learner to master new information to accommodate it (Piaget & Cook, 1952). Piaget’s early work was concerned with children, and he outlined four developmental stages- object permanence, pre-operational, concrete operational, and formal operational, which broadly speaking represent a developmental process from understanding concrete objects to being able to think abstractly. (Piaget & Cook, 1952) The ability to think abstractly is associated with a fully formed mental ability to adapt new information to existing schema. The core assumptions of constructivist learning theory are adopted in this work, and the concept of mental models and schemata are understood in relation to how game models impact them.

Experiential Learning Theory

Constructivist learning theory has supported many other theories that fall under its umbrella, proposing different mechanisms and patterns by which learners construct knowledge, such as experiential learning theory. The modern concept of experiential learning was outlined by Kolb in 1974, and is subscribed to by many researchers working in contexts that provide specific experiences to learners, such as occupational learning, museums, and games. Kolb explicitly built on the work of Piaget, Dewey, and Lewin. Dewey was interested in adult learning, and in his seminal 1938 work *Experience and Education* he addressed the tension between informal and formal education, and rather critiqued static teaching methods that did not

incorporate enough experience, and reflection upon it, “we do not learn from experience... we learn from reflecting on experience”. (Dewey, 1933, p.78) And from the psychologist Lewin, Kolb adopted his cycle of experiential learning, which Lewin developed based on his understanding of systems engineering (Lewin, 1951). The first assumption of ELT is that knowledge is constructed, and ELT takes a constructivist approach to understanding how learning occurs. Second, EGBL assumes that learning is a dynamic, active process involving direct learner engagement. Third, EGBL assumes that these processes are activated when learners participate in concrete experiences that provide opportunities for reflection and abstraction, and that knowledge and these experiences transform one another. (Kolb, 1974; Hutchings & Wutzdorff, 1988, Kolb et. al. 2001)

ELT expresses a cyclical model of learning, which has four stages, called i) concrete experience, ii) reflective observation, iii) abstract conceptualization, and iv) active experimentation. (Kolb, 1974, p.4) The cornerstone of this theory is “concrete experience”, which is a specific experience or encounter, or a reinterpretation of an existing experience, typically novel to the learner. Kolb theorized that learners could enter the cycle at any point, and learners can complete part of the cycle, all of it, or go through several iterations depending on the activity. The critical factor that sets ELT apart from other learning theories is “the important role that experience plays in the learning process, an emphasis that differentiates this approach from other cognitive theories of the learning process” (p.4). Kolb described two poles to this cycle- a “concrete experiencing”, in which a learner is immediately immersed in and dominated by an experience, and “abstract conceptualization” with learning involving the manipulation of symbols and images. (p.5) The other pole is active experimentation and reflection. An additional claim of experiential learning theory is that learners tend to focus on one of these diametrically opposed poles, to the detriment of its counter. As one example of evidence Kolb built upon in developing the theory, he noted that Singer (1968) found that children with rich imaginations and strong internal fantasy lives were more likely to delay action and Kagan et. al. (1964) that learners with very active orientations to concrete tasks do less reflecting, and have reduced development of analytic concepts.

Many elements in Dewey’s philosophy and theory of learning highlighted the role of context and experience in learning (and in doing so, helped articulate the emerging paradigm of progressive education). Dewey emphasized the importance of quality in learning experiences and highlighted the role

of social processes in learning. Importantly, Dewey also critiqued the “insular” classroom setting, in which learning is detached from real-world context, establishing a foundation for arguing for increased emphasis on experience and context. (Dewey, 1938) He was among the first modern learning theorists to argue that all genuine education comes from experience, linking knowledge to the “continual reorganization, reconstruction and transformation of experience” (1916, p. 50). Additionally, Dewey stressed that experience must have context to draw from it as educational. Dewey (1933) also developed deeper frameworks on the reflective component of learning, describing five phases of reflection in learning, from “suggestions”, when the mind moves forward to a potential solution, culminating in hypothesis testing with real or imagined action. The second of these phases invokes experience directly and consists of “intellectualizing” a problem that has been directly experienced into a specific articulated problem, a “question for which the answer must be sought”. (p.91)

Kolb also explicitly drew from the psychologist Kurt Lewin in articulating ELT, and his experiential learning cycle was modelled directly on Lewin’s own learning cycle as articulated in his work *Field Theory in Social Science* (1951). Lewin’s cycle of experiential learning began from direct experience with a phenomenon, which led directly to reflection, then concept formation, and culminated with testing in new situations. An additional explicit result of completing this cycle is behavior modification, so new experience choices can be made after each iteration of the cycle. Taking the assumptions of constructivist learning theory and Piaget’s description of the learning process as a cycle of interactions between learners and their environments, and integrating Dewey and Lewin’s concepts of experience and learning cycles, Kolb synthesized them into his modern articulation of experiential learning theory used by researchers.

Since Kolb articulated ELT in 1974, a significant body of research has developed practically applying ELT as a framework to explore learning in many domains. It has been applied and validated as an effective theoretical approach to designing and understanding learning experiences in the diverse domains of journalism (Brandon, 2002), agriculture education (Baker & Robinson, 2016), hospitality (Lee, 2007), and engineering (Chan, 2012), within both formal and informal learning contexts. For instance, Chan (2012) concludes learning experiences designed with Kolb’s ELT framework transformed and “internalized students learning experience, achieving a variety of learning outcomes” of engineering

concepts (p.405), and Baker & Robinson (2016) compared an experiential learning approach to an agriculture learning intervention, compared it to students using a classroom instruction approach, and found that agriculture students that undertook activities designed to facilitate Kolb's model scored higher on practical and creative assessment scores (whereas analytical scores were similar).

Games as Media

Games are an interactive media format that humans have used for millennia. Many similar definitions are offered by game scholars, with two prominent examples used in this work: "a game is a set of interconnected elements for structuring play" (Ralph & Monu, 2015, p.82), and Juul (2005) defines a game as a "rule-based system with a variable and quantifiable outcome" (p.36). Ralph & Monu describe the active process of "playing" a game as "an event wherein one or more players interact with the play-structuring system". (p.82). Games can be analog such as a card or board game (Schell, 2008), and embodied, or played with the physical self (Lee et. al., 2012). Games can also be digital, and played using a computer interface, as what is commonly called a "video game", a narrower type of interactive electronic media. Games are a media format in their own right and can also be an element in other learning formats or programs, such as part of a broader curriculum, or a museum exhibit. (Schrier, 2014) There is much afforded by game interactive media formats, including the ability to simulate other environments and scenarios (Squire et. al, 2004), receive immediate feedback (Kiili, 2005), the ability to fail safely and retry things (Gee, 2007), and the ability to conceptualize and immediately try new strategies (Gros, 2007).

While all types of games afford these features, there are unique affordances provided by video games that stem from the fact they are played with computers, the most central of which is "process intensity". Crawford (2003) defines process intensity as the degree to which a program emphasizes process instead of data, or in computer terms, "a higher crunch per bit ratio". All computer programs use a mix of processes (algorithms, equations, and branches), and data (tables, images, sound, text), and the more an application uses processes, the higher process intensity it has. This enables highly complex game programs, leading to more complex games that afford more depth. Meaningful learning occurs in all

types of games, however this work focuses on player experiences in complex game models, afforded by the process intensity of video games.

Game Based Learning

Game based learning (GBL) is the practice and phenomena of using game platforms to provide learning experiences within simulated game systems. (Prensky, 2000; Gee, 2004; Squire, 2005) Game based learning (GBL) is also a field of research and practice of increasing interest to scholars and practitioners, due to its potential to advance learning in novel ways using interactive media. (Ketelhut & Schifter, 2011) Game based learning describes the practice of using game systems and mechanics for learning, by embedding information and concepts about a domain in a game system (Prensky, 2003). The games used in GBL can take the form of analog games, such as traditional card or board games, or can take the form of more complex multimedia artifacts, such as video games (Deterding et. al, 2001). In GBL, information about a domain is represented in an abstracted form in some manner within the game itself, and modeled as elements of the game, such as components, rules, and systems, with which players interact. (Lankoski & Bjork, 2013) Typically, some type of goal structure is integrated with the model of the domain of knowledge represented in the game, and players interact with the game to accomplish goals and otherwise “play”. (Landriscina, 2013). The increasing use of GBL in a wide range of settings has generated interest and a body of research on numerous aspects and dimensions of these media as learning interventions, such as understanding effective learning game design principles (Gee, 2007; Klopfer et. al, 2018), games as motivating learning (Malone, 1981), understanding games as models for learning (Gee, 2004), games as environments for situated learning (Dede et. al., 2004), games as environments for social learning (Barab et. al., 2007), and studying cognitive approaches to games (Blumber, 2011).

GBL is frequently contrasted with “gamification”. According to Deterding et. al. (2011), gamification is “the use of game design elements in non-game contexts”. (p.9) Examples of gamification include game show style trivia games, leaderboards, “badges”, and systems of points and awards used to structure and motivate learning activities. Game systems typically contain gamified elements such as scores, but other contexts can employ these methods as well, such as leaderboards in work

environments, trivia systems in classrooms, and badges in digital business review applications.

(Deterding, 2011) Gamification is often associated with extrinsic systems of motivation, while game-based learning is associated with intrinsic motivation. Many scholars also use the term gamification to describe the task of taking such activities from non-game contexts as math worksheets or Spanish verb conjugation drills, and digitizing and integrating them with game elements (cte). While the term “gamification” is still sometimes used interchangeably with the term “game-based learning” in some scholarship and media, this work adopts the notion of GBL offered by Prensky (2000) and Gee (2004), which focuses on the elements of the games that themselves compose knowledge structures. In part in response to the critiques of edutainment and the shortcomings of many educational video games, and the narrow concepts of gamification as systems of motivations and rewards for participating in learning activities in games, scholars have turned their attention toward new ideas of what constitutes good learning in games, and what good game-based learning. The result is a large and growing domain of interdisciplinary practice and research that can be approached and understood through many perspectives and theories of learning.

The Foundations of Game Based Learning

Plass et. al. (2015) reviewed a large body of work on GBL and articulated four key “foundations of game-based learning” describing key aspects of the practice, each supported with associated research. These are the motivational, social, affective, and cognitive foundations of game-based learning. This team addressed the unsolved problem of creating a universal theory of game-based learning and noted “problematic is the attempt to formulate a general theory of game-based learning, as games can be designed based on virtually any model of learning”. (p.262) They instead propose a simplified model of game-based learning, claiming instead that the unique aspects of GBL are that game designers are uniquely concerned about the quality of the experience and that games can engage learners on levels that few other learning environments can. Each of the four foundations they posit provides a unique perspective from which GBL can be understood.

The motivational foundation of game-based learning refers to the aspects of games that support learner engagement and motivation, such as incentive systems, engaging narrative, and interesting

mechanics. The motivational foundation of game-based learning has the most in common with gamification and edutainment, and its explanations inherit some assumptions and principles of behaviorist traditions such as mechanisms of reinforcement (Loftus & Loftus, 1983; Graham & Weiner, 1996). Plass et. al (2015) draw from several theories of motivation to support this foundation of game-based learning, such as expectancy-value theory (Wigfield & Eccles, 2000), self-determination theory (Ryan & Deci, 2000), self-efficacy theory (Schunk, 1991), attribution theory (Weiner, 2012), achievement goal orientation theory (Elliot, 2005); and interest theory (Schiefele, 1991). They argue that current understanding of motivational aspects of game play for learning are broader than earlier behaviorist interpretations and design goals of game motivation. For example, Eccles, Wigfield, and Schiefele (1998) framed achievement motivation as people asking three questions- "Can I do this?" "Do I want to do this, and why?" and "What do I need to do in order to succeed?". (p.268) Plass et. al. argue that video games are well suited to address these questions in many ways. For instance, game designers create games to explicitly provide a positive answer to "can I do this?" via intentional design to facilitate achievement and allow for safe failure, and by providing clear scaffolding, tutorials, and in-game systems players can answer the third question "what do I need to do"?

Plass et. al. describe the affective foundation as focusing players' "experienced emotions, attitudes, and beliefs and considers how the design of the game environment impacts learners' affective state via affective engagement". (p.270) This careful attention to affective design is noted as one of the unique factors to which game designers pay special attention. This is achieved with design elements such as narrative, mechanics, musical score, and overall aesthetic design intended to engage learners. This view is supported by a range of research linking these design elements to player emotional states, and by showing that the positive emotions achieved by these design elements expand cognitive resources (Fredrickson & Branigan, 2005; Isen, 2002), link improved cognition to achievement emotions (Pekrun, 2000), and connect the unique role of multimedia design to emotion and learning (Plass & Kaplan, 2015). In this way, the affective foundation of GBL supports learning by using game design elements that provide emotional states and positive moods that support and enhance the learning experience and promote continued engagement.

The sociocultural foundation of game-based learning acknowledges that learning is socially constructed and motivated, and details how games “include opportunities for social engagement and provide contexts where peers and social interactions occur to enhance learning”. (Plass, 2015, p.272). The theoretical underpinnings of this foundation come directly from sociocultural learning theory (e.g. Bandura, 2002; Barab & Duffy, 2000; Wenger, 1998), and are supported by games and learning research that find and detail the manner in which games can facilitate social learning (e.g. Squire, 2006; Ito et al., 2008). For example, games are described as social spaces where players can participate as part of a community, and participatory learning culture emerges wherein communities’ members help one another by providing information, hints, and social support. (Leander and Lovvorn, 2006); Newman, 2014) Game communities also form as communities of practice (Lave & Wenger, 1991), wherein a players (a community) share expertise and interest in a domain of practice (a specific game), and develop standard practices, and even detailed methods of apprenticeship to learn expectations and skills. (Pearce et. al., 2011; Windleharth et. al., 2020)

This research concerns itself primarily with the cognitive foundation of game-based learning. Plass et. al. (2015) note, “the goal of learners’ engagement with a game is the construction of mental models”. This fundamental view, and its constructivist underpinnings, are addressed in Chapter 1 as a central concept in this work and is supported by a range of learning theorists (see Mayer, 2005). In video games, players take game elements they experience, arrange them in working memory, and integrate them with one another and prior knowledge. (Mayer, 2014) Plass et. al. state it is once again the role of the designer to determine how the knowledge and information should be represented, and how learning mechanics should be created to have the intended learning outcome. Many factors impact how players work through games and build mental models, including the cognitive load required to process the game elements (Kalyuga et. al., 2009), the amount of scaffolding as articulated by Wood at. al, 1976, in this case the way a game tutors or orientates players, and the form important information concepts take in the game and their function in the game and learning process (Carney & Levin, 2002; Plass, Hamilton, & Wallen, 2004).

In addition to the fundamental goal of integrating knowledge and constructing mental models, the cognitive foundation of game-based learning integrates several principles and theories of learning. A well-

designed learning game can utilize the principle of “situatedness” (Lave & Wenger, 1991; Wenger, 1998). Situatedness refers to the manner that the mind is impacted in the way it functions by the environment in and context in which it is operating and learning that is situated in a similar context is referred to as “situated learning”. Games can create meaningful virtual environments with elements that represent objects and features meaningful to a “real” context. The components of a game, the art, the scenarios, the narrative, and the representation of objects and ideas, and their relationships to one another.

Experiential Game Based Learning

The introductory section in this chapter on experiential learning begins by listing three key assumptions of ELT. Experiential game-based learning (EGBL) builds on this by extending the assumptions of ELT to a specific type of experience, drawing in and describing the intersection of these assumptions with the complex interactive media experiences afforded by games and game-based learning environments. (Kiili, 2005) Experiential game-based learning makes several assumptions about learning, several of which it inherits from its constructivist, experiential basis. The first is that knowledge is constructed, and it is a constructivist approach to understanding learning. Second, EGBL assumes that learning is a dynamic, active process involving learner engagement. Third, EGBL assumes that people learn when they participate in concrete experiences that provide opportunities for reflection and abstraction. Fourth, games can be designed to facilitate the complete experiential learning cycle. EGBL assumes games can be designed to facilitate the complete experiential learning cycle in a simulated environment, and that as a media format game provide unique experiences tied to the affordances of interactive simulations. These assumptions heavily engage game design and form, as “the main purpose of the model is to link gameplay with experiential learning” (Kiili, 2005, p.18). A major goal of this is to facilitate a state of flow for players through design, as well as describe learning as “a cyclic process through direct experience in the game world”. (p.18)

At the core of the model are the challenges posed by the game, based on educational objectives. (Fig. 2) This core (or “heart”, as Kiili calls it), directs challenges to the player, which serves to sustain motivation and engagement. Two cycles loop back and connect to the heart of the system. One loop is

the ideation loop with two nodes, the first being a “preinvative” idea generation node, and the second being an idea generation node. Preinvative idea generation is described as a chaotic, unstructured phase often resembling children’s play (Maslow, 1963). Preinvative structures are generated without consideration for system constraints (Finke et al., 1992), in this case without regard for the game components, mechanics, or rules. After this node, players then begin to consider the constraints and available resources and refine ideas in the “idea generation” phase. It is worth stress that the “constraints” and “available resources” noted here specifically refer to the game model as constructed by the designers and composed in its formal elements. This idea loop leads back to additional challenges at the core of the model, and the idea generation occurs in tandem with the broader experiential learning cycle.

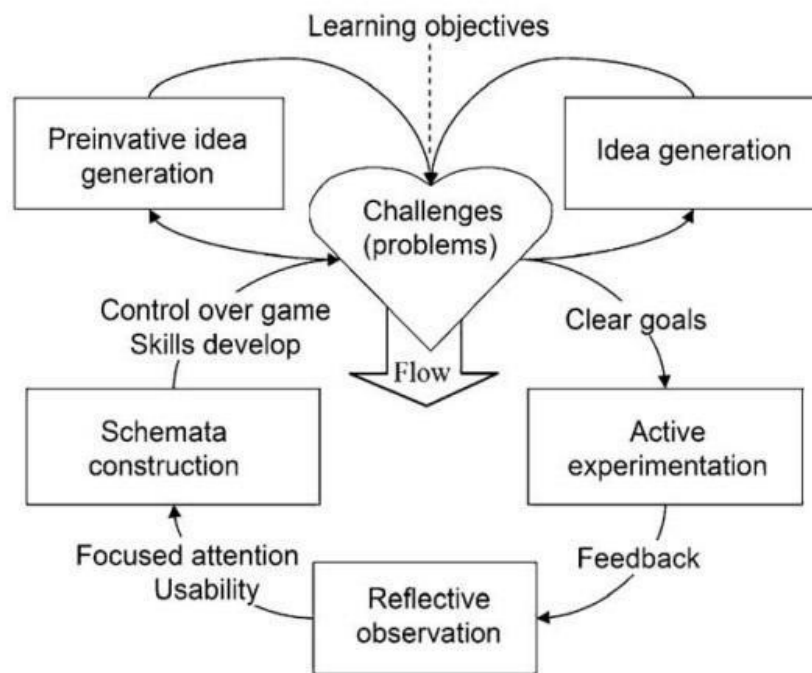


Figure 2. Experiential game-based learning model (Kili, 2005)

The second “greater” loop in the EGBL model is the experiential learning cycle. Ideas from the ideation loop are executed as concrete experiences and can take various forms depending on the design of the game. This leads to active experimentation with ideas and permutations of ideas, with the game providing some manner of feedback that the player can then reflect on, representing the reflective observation node in Kolb’s cycle. According to Kili, “the reflective observation of the feedback may lead

to the construction of schemata". (p.19) From here, the experiential cycle is completed with the abstraction of schema, leading back to the core gameplay challenges and gameplay loop.

Eng (2017) also elaborates on Kolb's experiential learning cycle, and similarly plots game attributes to each node in the cycle. For instance, Eng notes games provide Concrete Experience by using applied knowledge within game decisions, and that games incorporate Active Experimentation in the form of turns, actions, and activity cycles. Eng notes that games facilitate Abstract Conceptualization by players trying to discern game objectives and goals, and that games provide opportunities for reflective observation based on the results of actions and activities.

In a more general sense, many game based learning scholars focus on experiences as the basis of learning, even if GBL For instance Gee (2004) notes the term "wedding" is given meaning not only by reading a definition, but by experiencing and reflecting on weddings one has been to and applies this principle to games as useful experiences for constructing meaning. Scholars describe this mode of learning as lighter in explicit expository detail, but denser in application. "In experiential learning, students develop intuitions that are likely to be tacit and inchoate. They are important experiences, but they may not have the verbal mediation that translates into answering abstract or general questions". (Arena & Schwartz, 2013, p.538) Still, games provide an alternate set of simulated experiences for students to draw upon and provide a meaningful framework for offering problems to students. (Kiili, 2005). As games and learning scholar Kurt Squire once stated, "games are among the oldest forms of experiential learning." (Squire, 2007)

Many researchers have used experiential learning, both in the general framing of the Kolb learning cycle, as well as within the specific framework of EGBL. Much of the early work examining experiential learning and games was done in an occupational context. In 1998 Herz & Mers conducted an experiment with business students, and examined economics learning using the learning game MACRO, and compared it to a control group that used traditional classroom instruction. Participants answered 22 questions on a measure of aspects of the learning experience, the team found that the experiential cycle supported learning and the four learning stages more than traditional classroom learning. Ahn (2008) conducted a similar study with business students at a Korean university, focusing specifically on the Reflective Observation and Abstract Conceptualization stages of the learning cycle. Students completed

a set of questions rating their strategy and knowledge about concepts, and students who were engaged both in the reflective observation step and the abstract conceptualisation step of the learning cycle received higher scores in a knowledge application posttest than students who only engaged in reflective observation. These students also performed better in the business simulation game and had higher scores on a separate self-reported measure of their attitude toward the learning experience.

In 2001, Washburn & Gosen concluded learning took place in a computer simulation of MICROMATIC business and forecasting simulation, concluding it was a valid experiential learning activity. Feinstein (2001) used a food service operation game called FIST, and found greater learning from the experimental group that played the game, compared to a control group. Dickenson & Faria (1997) in studying business simulations, created a measurement method for evaluating learning called “random strategy criterion”. In this method, intentional choices by players in a game are compared to “random strategies”, with hypotheses being tested by comparing player and random scores. They tested this concept with 660 students and concluded that higher scores from sequential rounds of play indicate players were indeed learning in the game experience. In 2004, Washburn & Gosen conducted a review of the literature available at the time, citing these and other studies, and concluded that the reviewed empirical research supports the validity of experiential learning in simulations and games, but that there was a dearth of standard methodologies and additional research was needed.

In 2005, Dieleman & Huisingsh examined aspects of learning in the sustainability domain and integrated the concepts of experiential game-based learning. They reviewed the use of several games on sustainability, such as *Fishbanks Ltd.*, about sustainable fishing, *Triangles*, about interdependence of system elements, and *Avalanche*, about sustainable development. They compare game-based learning within these games to experiments and conclude that experiential game-based learning has additional benefits beyond regular experiments, “the added value of games compared to experiments is the fact that within games, one can combine aspects of comprehension and apprehension, as well as processes of intention and extension”. (p.841) In other words, games simultaneously focus on specific features supporting “understanding” and “experiencing”, “internalization”, and “externalization” in a manner facilitated by the game design. In the medical domain, Koivisto et. al. used EGBL theory as a framework in a qualitative study to examine nursing students’ learning when playing a 3D simulation game. This

team concluded that the experience of authentic scenarios and interactivity supported patent related experiences, and game related feedback was found to support student reflection on their learning process.

Kiili et. al. (2006) evaluated the component of his experiential game-based learning model with a design usability learning game called *IT_Emperor*, with 221 university students participating, and found matched challenges, clear goals, unambiguous feedback, and a sense of control as provided in games were important antecedents of flow and therefore learning in the EGBL model. Other researchers have also explored the efficacy of EGBL. Yang (2012) conducted a quasi-experiment with 9th grade Civics and Society students, with one group receiving a game-based learning experience using the commercial game *Tycoon City: New York* and one receiving only classroom instruction. Yang found that experimental group scores were higher than the control group, the experimental group reported higher motivation than the control, and concluded the results supported experiential learning as articulated by Kiili (2005). Hwang et. al. (2016) studies learning in a game called *Motion Math: Hungry Fish* and concluded that Kiili's flow antecedents in tablet & PC game-based learning contributed to flow and learning in their experiment. And Sung et. al. (2017) Kiili's EGBL model with a game designed in Enterbrain Interactives game designer *RPG Maker*, designed to teach the *Analects of Confucious* to elementary school students. In this experiment 49 students were divided into experimental and control groups, and data were collected with two measures, the validated measure MSLQ (motivated strategies for learning questionnaire) and an assessment of conceptual knowledge of the texts. They concluded "results showed that the students who learned with the experiential gaming mode showed higher learning motivation, better conceptions of deep learning strategies, and higher acceptance of the learning technology than those learning with the conventional technology-enhanced learning approach". (p.151) However, in this study no difference in assessment scores was found between the two groups. In addition to studies exploring the validity of experiential learning in games, and aspects of EGBL as articulated by Kiili, some creators and scholars have used Kiili's model as an explicit guide to make games (e.g. Handriyantini, 2017; Sung et. al., 2017).

While there is evidence validating experiential learning and EGBL, and the conclusions of a preponderance of scholars hold that it has merit, there are periodic calls for additional research into

various aspects of experiential learning and game-based learning. One example is the role of debriefing. Crookall (2010) firmly believes that more research is needed on the debriefing process of the experiential learning cycle predicated on games, stating “debriefing as the real fount of learning in simulation/gaming needs to become a central object of research in as many research projects as can reasonably and coherently accept them.” (p.915) Crookall stressed the importance of debriefing, as it benefits learners after completing a game-based learning experience, specifically referencing the reflection component of Kolb and his experiential learning cycle. At the conclusion of the 40th anniversary symposium of the journal *Simulation & Gaming*, Crookall made a point to highlight that most articles and journals on games and learning no longer mentioned reflection or debriefing of any type, specifically referencing Kolb’s experiential learning cycle. Crookall draws a harder line between the experience of playing a learning game and debriefing in terms of when learning occurs, stating “some serious and other gamers seem to have forgotten that the learning comes from the debriefing, not from the game” (p.907). Many scholars emphasize the reflective (or debriefing) component as more central to a game-based learning experience. However, most also appear to also recognize the learning potential of the gameplay itself, as well as the fact that reflection can take place even with the absence of a formal debrief. In Crookall’s own practice, his debriefing process takes more time than playing the game itself.

Games as Models

An important characteristic of games designed for game-based learning is that they in some way present models of real-world systems and phenomena. Many scholars frame it in terms of models of real-world systems, focusing on different expressions of the concept (see Gee, 2005; Shaffer, 2006; Klopfer et.al, 2009; Bogost, 2008) Gee (2005) uses “fish tanks” as a metaphor for game systems as models. As Gee describes them, fish tanks in the real world represent a simplified aquatic ecosystem where a few critical variables and their interactions can be highlighted, without being overwhelmed by a larger system. Fish tanks represent good models of more complex aquatic ecosystems, and when used in a learning context can provide learners an opportunity to “see some basic relationships at work and take the first steps towards their eventual mastery of the real system”. (p.12) In this way games are like fish tanks, and

indeed introductory parts of games can even serve as “fish tanks” to prepare players for more complex parts of the game.

Schaffer (2006) describes how game models can be designed with complex simulations that represent professions with high fidelity, which is the defining characteristic of a class of games he calls “epistemic games”. Epistemic games model tools, actions, and scenarios pertaining to a specific occupation in the real world, such as firefighting, stock trading, or piloting. In epistemic games, all of the elements of the game are intended to minimize abstraction of concepts and maximize design decisions that represent objects and actions in the real world with high accuracy. As a result, the models of systems in epistemic games tend to be among the most realistic and concrete among learning games.

Bogost (2008) describes game models intended to persuade players, and otherwise represent a particular view of the world, through a process which he terms “procedural rhetoric”. Bogost notes that “video games are usually created with some expressive purpose in mind; they represent models of systems or spaces that players can inhabit”. (p.122) He also adds, “when we build models, we normally attempt to describe the function of some material system accurately”. (p.125) Bogost expands on this concept by outlining how game designers make decisions about procedures in a game that make claims about a particular worldview, entering the realm of rhetoric. For instance, he describes the game *Animal Crossing* as “a game about everyday life in a small town” and expands on this to note it is “also a game about long term debt. It is a game about the repetition of mundane work necessary to support contemporary material property ideals”. (p.119) Bogost also notes that the design of *Animal Crossing* doesn’t use “moralistic regulation” to accomplish its rhetorical aims, but rather it is built on “a model of commerce and debt in which the player can experience and discover such consequences” for themselves. (p.119)

The concept of games as models to be explored and experienced by players is central to this work. This research focuses significantly on the compositional (or formal) elements of game models, their relationships, and the systems they create. It seeks to understand how players interact and come to understand the model through these elements and make meaning and adjust their own mental model (schema).

Preparation for Future Learning and Transfer

One additional function of experiential game-based learning experiences that researchers have articulated is the concept of “preparation for future learning” (PFL) (Bransford & Schwartz, 2001). This describes the benefit gained from exposure to a collection of concepts, ideas, and relationships gained from experiences. While a learner may not develop full understanding from an experience, they may gain a form of “inchoate” knowledge which serves as an experience to reflect upon and support additional learning about the topic when it is encountered again in the future. It is closely connected to Kolb’s ELT as it builds on the work of Dewey (1938), in that it also claims that learners use their prior experiences as one element of constructing knowledge. As Hammer & Black (2009) note, “players develop a body of knowledge about how systems work that they absorb from games but cannot necessarily articulate”. (p.30)

Scholars that research PFL often relate it to the concept of “transfer” in learning. Transfer refers to learning in one context that enhances or reduces learning in another context (Ellis, 1965; Perkins & Salomon, 1992; Haskell, 2000). There are three key facets to a learning transfer outcome, which are direction, proximity, and mechanism. With direction, “positive transfer” refers to learning in one context enhancing learning in another context, and “negative transfer” refers to hindering learning in a new context. (Sears in Pepler, 2017). With proximity, transfer is referred to as “near transfer” if it pertains to closely related contexts, and “far transfer” if it refers to very different contexts. (Perkins & Salomon, 1992) And with regard to mechanism, reflexive (or “low road transfer”) is realized by drill, routine, and stimulus and mindful (or “high road transfer”) is realized by “deliberate effortful abstraction and a search for connections”. (Perkins & Salomon, 1992, p.2) In this way, many “drill and kill” games and other arcade style learning games relying on similar gamification elements rely on low road transfer to reinforce learning. Conversely, “game-based learning” as discussed by more recent games and learning scholars focuses on “high road transfer”. Some game scholars have explored transfer of learning between games and non-game contexts (e.g. Green et. al., 2010A; Looi et. al., 2016). For instance, de Gortari & Griffiths (2011) have referred to transfer between and from game contexts as “game transfer phenomena” (GTP), Shaffer (2006) explicitly proposes a mechanism of transfer in his epistemic games framework which is

supported by the theory situated learning in occupational games, and Green et. al. (2010B) explore transfer of several aspects of visual perception learning from video games to other contexts.

Bransford & Schwartz (1999) developed the concept of preparation for future learning by directly building on shortcoming so research on transfer of learning. They aggregated the body of work on transfer, and looked for evidence of transfer or lack thereof, motivated by the mixed findings in research seeking transfer. Broudy (1977) argued that the problem with efforts to measure transfer is not necessarily that transfer fails, but to find it requires a reconceptualization of what constitutes transfer. Detterman & Sternberg (1993) put the concept of “transfer” on trial, arguing both for and against it while highlighting inconsistent findings on research that evaluates transfer. Bransford & Schwartz argued that theories and methods measuring transfer work well for high levels of expertise but are too “blunt” to find what researchers are looking for, and that interventions under investigation frequently consist of “sequestered problem solving”, which can hide potential benefits from learning outcomes research. This led to the development of the preparation for future learning framework (PFL).

In conceptualizing PFL, Bransford and Schwartz (1999) proposed a novel measurement paradigm for learning outcomes of experiences, including game-based learning, which they call a preparation for future learning measurement. In traditional assessments, learners are sequestered away from external resources, and tests typically lack the sensitivity to measure PFL. (Reese, 2007) In a PFL evaluation, students receive learning resources as part of the overall assessment, and the method probes whether prior experiences prepared them to learn from these resources. PFL measures examine learning outcomes of students that are exposed solely to a “learning resource” such as text or lecture, and those who had a prior PFL experience (including learning games) in addition to the learning resource. In these assessments, students are placed in an environment with an outcome evaluation that is not solely sequestered problem solving. In PFL, learners are provided with a concrete experience that introduces an abstracted version of the learning, and then given subsequent instruction or reference materials.

Several studies have found that experiential learning interventions, including those based on video games led to better outcomes in the PFL case, even when measures with sequestered problem solving showed no difference. For instance Arena & Schwartz (2013) used a video game called *Stats Invaders!*, based loosely on the 1978 Taito game *Space Invaders*, which models enemy spaceship attack

patterns in the form of statistical distribution curves. In the study, a sample of community college students that read a passage on the statistical patterns and also played the game outperformed students that only read the passage. There is a growing body of evidence that experiences in game-based learning environments can prepare people for future learning by providing that inchoate knowledge represented in the game model. (Arena & Schwartz, 2013; Bransford & Schwartz, 1999; Schwartz & Bransford, 1998; Schwartz et al., 2005; Schwartz & Martin, 2004; (Hammer, Black, Andrews, Zhou, & Kinzer, 2007).

Formal Analysis

Formal analysis of games and gameplay is an analytical method for understanding the core elements that compose a game, their attributes, relationships with one another, game mechanics and rules, systems they compose, and the overall structure of a game. (Lankoski & Bjork, 2015). Formal analysis of games plays a critical role in this work, by serving as a structured means of understanding the underlying model of a game as represented by specific components, actions, rules, and their relationships. The methodology of this work (see Chapter 3) uses think aloud reporting in conjunction with gameplay to link micro-scale interactions with specific thought processes and ideas during the process of meaning making. While not strictly a “unit of analysis” in the sense described by Czauderna & Guardiola (2019), these small scale interactions, continuously monitored and described in a controlled manner, will help facilitate “close monitoring of the interconnections between gameplay and learning at the micro level of players’ actions” (p.219)

A key characteristic of formal analysis is that it is detached from interpretation and meaning of an artefact or work, and focuses on describing the elements of a work and their relationships in a systematic manner, with controlled language. Formal analysis has its origins in art criticism, with British art critic Roger Fry among the first to describe the practice in detail. (Fry, 1920; Fry & Bullen, 1998) Fry sought to set aside the focus on interpretation and meaning of art and focus instead on the composition and elements of a piece that makes up its “form”. (Munsterberg, 2008) In this way, different observers would arrive at a similar analysis of the form of an art piece, even if their interpretation of its meaning differs.

As more art critics began to use formal approaches to describe works, the idea of articulating methods to analyze the forms of other media also began to emerge. A classic example is the work of Propp examining the form of Russian fairy tales in his work *Morphology of the Fairy Tale*, originally published in 1928. (Propp, 2010) Propp developed a method for describing the structure and formal organization of a folkloristic text, accomplished by plotting the linear sequence of events in the text, from the point of view of the informant. Among Propp's conclusions were that "five categories of elements define not only the construction of a tale, but the tale as a whole". Methods of formal analysis, and corresponding terminology to describe elements and values of elements, have been articulated for other media such as film (Bordwell & Thompson, 2008) and comics (McCloud, 1993; Carrier & Oliker, 2001; Miodrag, 2013).

The concept of formal analysis is being applied to video games, and several game studies scholars have articulated methods to understand the form of video games at various levels of description (Hunicke et. a). One such framework for formal analysis is the MDA (Mechanics, Dynamics, Aesthetics) framework articulated by Hunicke, LeBlanc, & Zubek (2004). MDA was explicitly designed for use by game designers, researchers, and scholars and "is a formal approach to understanding games, one which attempts to bridge the gap between game design and development, game criticism, and technical game research" (p.1). MDA is a broadly used framework for formally analyzing a "whole game" at a high level.

Formal Analysis of Games and Gameplay

Lankoski & Bjork (2015) have articulated a method for formal analysis of games and gameplay and has been adopted as the method of formal analysis for games used in this research. Lankoski & Bjork devised the method with the same goals as formal analysis of other media in mind, noting it "can be seen as a fundamental or underlying method, in that it provides an understanding of the game system that can in a later step be used for further analysis." (p.23) The method outlined in formal analysis of games provides the structure for describing and understanding the elements of the game in this work.

Formal analysis "focuses on different elements of a work, that is, asking questions about the elements that constitute the parts of the work, and the role of each element in the composition as a

whole” (p.24). The authors apply this design concept to analyzing games, noting “many contemporary games are too big to be described fully. Finding the parts of the games that are relevant for the current focus of interest is the first part of formal analysis”. (p.27) As such, this is a method for deconstructing and analyzing the elements of games, their attributes and values, and how they relate, to facilitate research at an appropriate level of detail to supplement to the broader framing of MDA. Game scholars have used formal analysis to analyze various aspects of games. For instance, Bjork & Holopainen (2005) used formal analysis to study game design patterns, and Myers (2010) used formal analysis to study the aesthetics of games.

Primitives are discrete game elements that are the basic building blocks of games, with the three major classes of game primitives being components, rules, and goals (p.25). Primitives can exist in several instances in the game, and each instance can have different values as allowed by the rules of the game. Components are primitives that are objects that an agent such as a player or computer can manipulate, or that define the game play space. In chess, components include the individual chess pieces, and the 64 spaces that make up the board and define the play space. In a game such as Super Mario Bros., example components are the Mario avatar, the blocks and bricks that make up platforms, the enemies such as goombas and koopas, collectable items such as coins and powerups, projectiles such as hammers and fireballs, and registers such as the coin counter and countdown timer. Additionally, each component may have different values (such as how many coins are in the coin register), or attributes (Mario being “powered up” with a fire flower).

Another key primitive type is an action. Actions are runtime processes that are executed in a game, and they come in three forms defined by where they originate- player, component, or system. (p.25). Player actions are the actions available to a player and involve manipulating or generating components. For example, in chess the actions available to a player are dictated by the number of pieces on the board, and their rules of movement. In Super Mario Bros., player actions are move left, move right, jump, shoot fireball, duck, etc. Goals are the final type of primitive and are defined by “what overall conditions of the game state have specific significance for the gameplay.” (p.26) Games typically contain both short term goals (such as avoiding enemy attacks), and longer-term goals such as achieving a checkmate in chess or defeating a final boss.

The collection of all primitives and their values define the game state (p.25). The term “game state” used here is synonymous with the term as used in classical economic game theory and programming, and is largely eponymous, describing all attributes of all elements in a game at a specific moment in time. For example, a description of a game state in chess would describe the positions of all the pieces on the board, and whose turn it is. A single frame of a video game also represents a game state, with each component occupying specific positions in the game space and having specific values.

Lankoski & Bjork detail the steps of conducting a formal analysis of game play, which is similar to decomposing other media artefacts into their formal components. The researcher asks guiding questions, such as “What happens when one does this? Does the same thing happen every time? What can one do in this situation? What cannot be done in that situation”? (p.27) The aim of the researcher is to identify and describe the relevant primitives for the study at hand, at the level of analysis that makes the most sense to answer research questions. A more detailed analysis of the relevant primitives and their relationships follows. Lankoski & Bjork identify three levels of description:

1. Describing primitives and their relations
2. Describing the principles of design
3. Describing the role of the primitives and principles of design in the game

These levels of description are sequential, and dependent on the lower-level descriptions, and there are additional properties and relationships at the first level of description that are necessary to move forward to the next level of description. For instance, in the game *Super Mario Bros.*, the entire game environment pushes down on Mario (simulating gravity). If this effect causes Mario to touch the bottom of the pit, he dies. However, if this effect causes Mario to land on top of a hammer throwing enemy, it dies. If an enemy weapon such as a hammer touches Mario in any way, he dies. Mario also has a relationship with the game space component. If Mario proceeds right, the game space component also moves right or “scrolls”. The description of these components and their relationships describe the first level of analysis.

At the second level of analysis, the principles of design are articulated using the results of the first level of analysis. For example, guiding the Mario component to defeat or avoid enemy and hazard components in *Super Mario Bros.* is a core design principle of the game and gameplay. Additionally, in the game “lives” constitute a resource that determines how many times Mario can “die” before losing the

game and must start over, as a design principle of “limited attempts” to add to the challenge of the game. To add further challenge, when the “timer” attribute of the game system reaches zero, Mario automatically dies and loses a life, representing a time-limited principle of design. The highest level of description in game formal analysis articulates the *role* of primitives and principles of design to the overall game. In this sense, in Super Mario Bros. the Mario component is guided through a goal structure of sequential levels, wherein Mario defeats enemies and avoid traps and reaches an end goal, within a given time limit. Describing the principles of design (level 2) and the role of the primitives and principle of design in the game (level 3) allows structured comparison of games (p. 27).

Formal analysis plays an important role in this work. Lankoski & Bjork note that formal description alone is not enough for a study, but rather “one needs to have a research question formulated, and the role of description is to help answer the research question”. (p.30) They also note, “the results of formal analysis can also be contrasted or tested against other sources, for example, information from players, designers, and reviewers”. (p.23) In this study, the formal analysis will represent the details and rules of the game as a formal representation of not only the game, but the abstracted model of real-world phenomena. The source against which the resultant analysis will be contrasted in this study is the mental model of the game made by players, created as they experience game play and make sense of the primitives, components, actions, and goals while experiencing the possibility space within the game.

Game Mechanics

For purposes of describing and understanding games, it is useful to understand game mechanics in further detail as a necessary tool in analysis of a game, and how the mechanics of a game works. In the MDA framework, mechanics “are the various actions, behaviors and control mechanisms afforded to the player within a game context.” (p.3) For instance, Hunicke et.al. describe the mechanics of poker as shuffling, trick taking, and betting, and shooter games containing mechanics such as weapon use, ammunition, and spawn points. Within the Lankoski & Bjork method of formal analysis, this concept is partly subsumed by the “action” primitive. Sicart (2008) defines mechanics as “methods invoked by agents, designed for interaction with the game state.” Sicart takes from Jarvainen (2008) the notion that mechanics are methods, and are formalized as verbs, with syntactical/structural elements such as rules

influencing the behavior of those verbs in the game. This approach, and the ability it grants to map these mechanics to inputs such as keyboards and controllers where applicable, allows “for a great degree of granularity in the analysis of games.” (Sicart, 2008, p.5) For analysis in this work, Sicart’s definition will be adopted and used in interpretive accounts of player data pertaining to mechanics. Understanding all of these formal elements and the action afforded to players in game via mechanics allows for controlled rich description, but additional methods are needed to understand why players do what they do, and what understanding they develop through the course of play. Sicart (2008) notes, “the formal, analytical understanding of mechanics only allows us to design and predict courses of interaction, but not to determine how the game will always be played, or what the outcome of that experience will be”. (p.7)

Research Approach

This research uses interpretative phenomenological analysis (IPA), a qualitative, inductive approach to understanding how people make meaning from complex experiences. Data for IPA will be collected through recorded think-aloud gameplay sessions, and pre and post gameplay interviews will be conducted. The game itself will also be analyzed formally and decomposed into its formal elements and systems for purposes of analysis and comparison. Rich qualitative data coding will take place, and results will serve to answer the research question: *how do middle school learners make meaning of game systems and components that model real world phenomena through their experiences interacting with them in game-based learning environments?*

Interpretative Phenomenological Analysis

Interpretative phenomenological analysis (IPA), the core approach used in this research, is a qualitative approach to exploring peoples’ personal experiences and how they make sense and meaning of phenomena. (Smith & Osbourne, 2003) By using the two complementary commitments of giving voice to participants and making sense of what that voice reports, researchers work toward understanding the meanings participants attach to particular experiences, which are the ‘main currency’ of IPA research.

(p.53) In the context of this work, the environment of the experience includes a simulated game world, and the phenomena under investigation are objects, systems, patterns, and behaviors reflected in the game simulation. Studies using an IPA approach can use qualitative data collected with many different methods, with interviews being the most frequently used. Data for this study will be collected from think-aloud gameplay sessions, as well as pre-play and post-play interviews with participants. Chapter 3 describes the complete method used in this research.

IPA is grounded in and has explicit commitments to three major concepts- phenomenology, hermeneutics, and idiography.

Phenomenology

Phenomenology is the “study of human experience and the way in which things are perceived as they appear to consciousness.” (Langdrige, 2007, p.10) It refers to the “appearances of things, or things as they appear in our experience, or the ways we experience things, thus the meanings things have in our experience”. (Smith, 2003, p.1). It is also explained as “the study of structures of consciousness from the first-person point of view” (Gallagher, 2012, p.7). Smith (2003) notes that phenomenology is distinct from but related to the fields of ontology (knowing what is), and epistemology (the study of knowledge).

Edmund Husserl is credited with founding the field of phenomenology and wrote prolifically on the topic and led early efforts to develop a “philosophy of phenomenology” (Husserl, 1970; Zahavi, 2003). In this “Husserlian phenomenology”, the lived body is the center of experience, and how it senses and moves plays a role in “how we encounter other embodied agents in the shared space of a coherent and ever-explorable world”. (Behnke, 2019, p.1) Husserl described all experience as the domain of phenomenology, defining experiences as things people “live through” or “perform”, and he contrasted experience with things such as “observation” and “engagement” which people do not live through or perform.

Hermeneutics

Palmer (1969) defines hermeneutics as “the study of understanding, especially the task of understanding texts”. (p.8) In IPA the researcher has an explicit role in the research task of uncovering knowledge, as

they are involved in the process of interpreting participant interviews and experiences, reflected in IPAs commitment to hermeneutics and interpretation. Husserl's student, Heidegger described hermeneutics as a prerequisite to phenomenology, and IPA explicitly links them both. Moran (2000) explains, "phenomenology is seeking after a meaning which is perhaps hidden by the entity's mode of appearing. In that case the proper model for seeking meaning is the interpretation of a text and for this reason Heidegger links phenomenology with hermeneutics." (p.229). Hermeneutics and interpretation are interconnected, and when practically applied they aim to clarify and restate embedded meaning. They aim "to make meaning intelligible". (Grondin, 1994. p.20)

A defining characteristic of IPA is its "double hermeneutic"- the process of the researcher making sense of participant interpretations. Smith & Osborn (2004) explain, "the participants are trying to make sense of their world; the researcher is trying to make sense of the participants trying to make sense of their world". In this study, middle school game players are trying to make sense of their game world, and the researcher is trying to make sense of the players trying to make sense of the game world.

Idiography

Idiography refers to a focus on individuals and their circumstances and perspective in research and analysis, as opposed to groups or populations. (Smith et. al. 2009) The focus on particular cases functions on two levels. The first is detail, which commits the researcher to a deep and thorough analysis of individual cases being studied. Second, idiography commits to understanding the perspective of particular people in a specific context. As Shineborne (2011) notes, "an idiographic approach aims for an in-depth focus on the particular and commitment to a detailed finely-textured analysis". (p.22) Shinebourne also differentiates types of research as "idiographic" and "nomothetic" depending on focus, defining "nomothetic knowledge as knowledge of general laws, and idiographic knowledge as knowledge about unique events, entities, and trends". (p.23) Idiographic research approaches can be important complementary methods to nomothetic research by providing insight using particular cases. As Smith et. al. 2009 notes, by connecting the findings to existing literature, "the IPA writer is helping the reader to see how the case can shed light on the existing nomothetic research". (p.38)

Appropriateness of IPA

IPA is a research approach that encompasses methods of qualitative data collection and analysis employed to understand a person's experiences with a phenomenon, their interpretation of it, and how they create meaning and make sense of it. IPA was chosen for this study due to the novelty of the approach toward understanding meaning making, its characteristics that are consistent with theory that guides this work, and references in existing GBL literature to a need for deeper qualitative analysis into the process of player meaning making in games. Game based worlds present players with novel situations and environments, and the process intensity of video games in particular enables simulations of complex environments and systems. Smith & Osborn (2004) describe IPA as appropriate to these characteristics, "IPA is a suitable approach when one is trying to find out how individuals are perceiving the particular situations they are facing... IPA is especially useful when one is concerned with complexity, process or novelty". (p.55)

Using formal analysis of games and gameplay is also supported by IPA. Smith (2008) notes, phenomenology addresses "the meaning things have in our experience, notably, the significance of objects, events, tools, the flow of time, the self, and others, as these things arise and are experienced in our "life-world". (p.1) The experiential aspect of interactive games, and the meaning made within this play directly represent the "meaning things have in our experience"- in the context of this study, the meaning of experiences in the game. Furthermore, the aspects Smith highlights as notable, "objects, events, tools, and flow of time" as key components of these experiences are explicitly designed elements within the game experience, that can be understood and expressed through formal analysis of a game. These arise and are experienced in the player's "life world", which includes the "game world" within the context of this study. In a learning game, these game-world elements- objects, events, tools, and flow of time are designed to integrate a model of a specific ontology, which players then experience and use to make their own meaning.

The focus on understanding a player's experience within the game world, in interacting with game components and systems, is consistent with game based experiential learning theory. Both EGBL theory and IPA share a focus on examining concrete experiences that can be interpreted and reflected upon. IPA further aligns with EGBL with the emphasis of each on understanding how subjects make sense of

phenomena and create meaning from the interpretations of experiences specifically. Miller (2018) ties the goal of IPA even more directly to experience, noting the fundamental goal of IPA is to “make sense of the participants making sense of an experience”. (p.11) For these reasons, IPA is well suited to answer the research questions posed in this research.

IPA, Games, and Meaning

The overall approach to this research is embedded in interpretative phenomenological analysis (IPA). This method is explored more fully in chapter 3. However, there have been a few studies conducted using IPA that shed some light on the approach as used with learning and games.

In the domain of math education, Pipule & Micule (2014) used IPA to examine the role of mathematical identity of teachers in service, and the relationship of this identity with how teachers perceived student relationships with and feelings about math. Major themes emerged around “instrumental interpretation of mathematics and its teaching methods, self-actualization in achieving success in mathematics through hard work, and the issue of attribution of failure in mathematics either to external or internal factors.” (p.5) These broad themes are explained in detail in the analysis and illuminate how math teachers make meaning from this concept. A few studies have also specifically used IPA to explore learning in games. In 2014, Rosenblum conducted an IPA study to understand what it is like for players to experience sound while playing educational games, and the role of sound in supporting the educational experience. The author found that music in the game helped provoke thought, in addition to providing emotional context for play, supported engagement, conveyed a sense of the game interface, and communicated narrative to the player. This study also linked concentration to music and found that when music was interrupted it would break player concentration and flow. This is consistent with Kiili & Lainema (2008), who state that concentration as an antecedent to flow experience in a game.

Alexander (2015) used IPA as an approach to understand how players use video games to satisfy the four basic psychological needs described in a framework called “choice theory”. In this study, the author developed patterns and themes around defining needs, and the results were intended to assist counselors in helping game players use this information to understand psychological needs better and

more efficiently. Choice theory is a psychological construct developed by Glasser (1998) and describes the four basic psychological needs people seek to fulfill- love/belonging, power, freedom, and fun/pleasure. The idea is that people can control their behavior to influence their mental health, and when people realize this, they can make choices to meet these needs and improve the quality of their life. Alexander (2015) examined the unique empowerment and choice inherent in most video games and used IPA to make sense of fundamental needs while playing games. Four major themes emerged, including social interaction, self-worth, accomplishment, and identity formation. (p.134) All players reported positive outcomes from gameplay, and all reported games as offering choices to fulfill each fundamental need through play in the gameworld.

Some work focusing on gambling has used IPA and intersects a body of game research. Nixon et. al. (2013) used IPA to examine the role that trauma plays in the development of pathological gambling. In this study, the authors conducted unstructured interviews with six women, and together they explored links between the impact of trauma on personhood, and how this subsequently contributed to the origin, progression, and loss of control in gambling. Five themes emerged that tied trauma to gambling, such as seeking distracting and soothing behaviors, and periodic winnings as short-term validation and relief from the “not good enough self.” (p.225)

Chappel et. al. (2006) conducted a study using IPA to create an account of online gamers who perceived themselves as playing the popular massively multiplayer online role-playing game *Everquest* excessively. Specifically, they wanted to understand how players perceived and made sense of the role of *Everquest* in their lives. The team concluded that most players appeared to be addicted to *Everquest* in the same way some people become addicted to alcohol or gambling. Additionally, major themes of the phenomena reported by players and interpreted by researchers “display (or allude to) the core components of addiction such as salience, mood modification, tolerance, conflict, withdrawal symptoms, cravings, and relapse.” (p.205).

Advancing Understanding of Player Meaning Making in Games

In reviewing the literature on experiential computer-based simulations and games, Gosen & Washburn (2004) conclude that these interventions are effective, but “the criterion variable being used,

which is learning from a computer-based simulation or experiential exercise, is illusive. To our knowledge, every attempt to concretize this variable has failed... what it looks like so it can be measured lacks form". (p.284) They highlight that learning is an internal process unique to each individual. To get at this learning, learners must be motivated to express their learning, and a post intervention test might not be enough to express this learning. It is in this light that this work is undertaken using the method of interpretative phenomenological analysis supported by think aloud gameplay, as they are methods uniquely suited to highlight this "internal, mental process".

Much of the research in games-based learning has been conducted with quantitative post-test assessment and similar evaluations of knowledge and skill acquisition. In most cases, data is collected before and after an entire game intervention. Bransford & Schwartz (1999) once described efforts at measuring learning and transfer, "too blunt" (p.66). And Gee (2003) critiques methods of research exploring play, stating that too many relied on "the result" of gameplay, focusing too much on narrow outcomes. Gee states that "playing and learning are highly interconnected categories of analysis", and that learning is a process that must be explored. Czuderna & Guardiola note even in 2019 that generally "player actions are not assessed individually, such that each action a player executes is examined for its contribution to the whole learning experience". (p.209) They also observe that interactions with the game state are typically observed "superficially", over the course of single or multiple sessions. Little work has been done looking at this micro-perspective of players, or learners' actions in as they unfold in a game, "most approaches lack a micro-perspective of players', or more specifically learners' actions in sequence – including their learning potentials (while taking into account the challenges of the game)". (p.209) And in highlighting the potential role of formal mechanisms of gameplay in exploring learning, Czuderna & Guardiola note a critical gap in the literature, "the neglect of the unfolding of gameplay through players' actions over a short period of time as a unit of analysis". (p.209)

These and similar sentiments in the literature underscore a gap in understanding these processes, and a review of the literature did not reveal any research that has been conducted in this space. Few studies have qualitatively examined thinking throughout the play process. This novel research will require a qualitative methodology, a data collection mechanism to continuously collect information

about subject thoughts through play sessions, a controlled system to describe formal structures the players interact with, and an approach to analyzing data that explores meaning making processes.

Chapter 3: Research Design and Methodology

The core design of this research was facilitated by interpretative phenomenological analysis (IPA), a qualitative approach to understanding how individuals make sense of phenomena and experiences. IPA relies on rich interview data from research participants about the phenomenon under question, which is then interpreted by the researcher and organized into meaningful conclusions. (Smith, Flowers, & Larkin, 2009) In this dissertation, research subjects engaged in play sessions of the simulation game *Oxygen not Included* as the primary intervention, and the primary source of data was a think-aloud interviewing process that took place throughout the duration of play of gameplay sessions, and the transcripts corresponding to these play sessions. Participants also provided demographic data and participated in pre-play and post-play semi-structured interviews to supplement researcher understanding of domain material and their orientation to game-based learning. The range of data facilitated insight into changes in understanding of concepts present in the game, how that process occurred, and explored the broader game play experience. In IPA, the researcher has an explicit role in the data generation process by interpreting the information reported by informants, and extracting meaning ascribed by participants to the phenomenon under question. (Smith & Osborn, 2014) This interpretation of informant reporting is therefore subject to a “double hermeneutic” process, as it is a reading and interpretation of informants’ own interpretation of the experience. Data was organized in and analyzed using the software package NVIVO 12, and findings will be organized into superordinate (main) and subordinate (child) themes. The research result is a rich description of these themes linked to examples from the data from which they were generated, which serve to answer the research question and form conclusions. An overview of the research process is reflected below in figure 3.

The research process consisted of five phases, encompassing four data collection instruments. The first phase of the study involved subject recruitment and consisted of reaching out to middle school students with assistance from a local school board member, and collecting initial data with a survey

instrument. A purposive sample of twelve subjects was assembled based on these initial survey responses. Subjects in the assembled sample then participated in semi-structured pre-gameplay interviews using a second instrument detailing the interview protocol and guiding questions, designed to generate information about the subjects' experience, understanding, and approach to navigating game environments, as well as some basic ideas of their understanding of domain knowledge represented in the game.

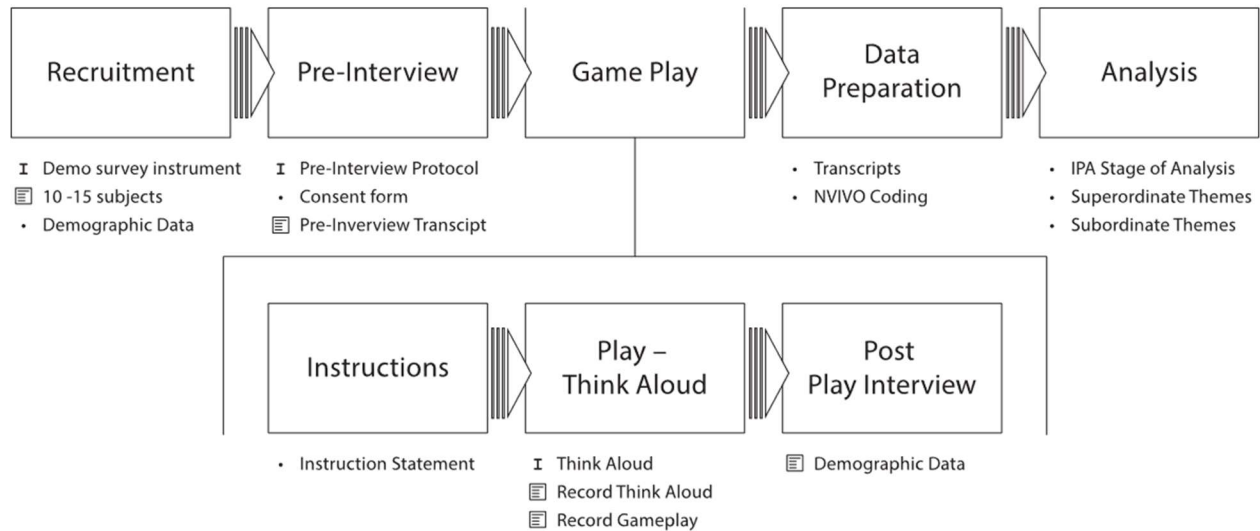


Figure 3. Visual outline of dissertation research process

The “Game Play” phase represents the largest source of data, as it consists of the gameplay experience itself, and provides the data most central to answering the research question. Appendix E provides more details about *Oxygen not Included* and its components and systems. The game play activity consists of three steps that are completed together in sequence, for each game play session for each subject. First, an instruction statement is read to each participant and a short warm-up activity will be conducted. Then the player engages in a think-aloud gameplay activity in conjunction with the researcher using the think-aloud protocol instrument and its guiding questions. Think-aloud activities involve asking a participant to continuously discuss what they are thinking, and why they are doing what they are doing, to understand internal thought processes. In this study, this will help elucidate player thinking, ideas, strategies, feelings, and thoughts in general, especially as they pertain to making sense of the game components and model. After game play, subjects will participate in a final post-play semi-

structured interview with the researcher, representing the fourth and final data source and collection instrument. The post-play interview is used to further explore player meaning-making strategies, clarification, and helps triangulate data from the game play sessions.

The fourth phase of the methodology is data preparation, which includes generating transcripts for the interview and think aloud sessions, and loading all survey data, audio and screen recordings, and transcripts into the software tool NVIVO 12 for use in analysis. The fifth and final phase of the methodology is the analysis, which involves rich qualitative coding of the data, and generation of superordinate and subordinate themes within the framework of IPA, along with rich descriptive examples tied to the game model and form. Together, these results serve to answer the research questions and provide conclusions to the study.

Interpretative Phenomenological Analysis

The methodology in this study is situated in the framework of interpretative phenomenological analysis (IPA), which is an approach designed to understand the “essence” of a phenomenon being studied and how people make meaning from these phenomena. (Smith, Flowers, & Larkin, 2009) According to IPA framers Smith & Osborn (2012), the purpose of IPA is to “explore in detail how participants are making sense of their personal and social world, and the main currency for an IPA study is the meanings particular experiences, events, states hold for participants”. (p.53) This approach was originally developed for understanding experiences and interpretation of phenomena in subjects’ lives, including social contexts such as work and home, and was extended by Smith & Osborn and subsequent researchers into understanding other types of meaning making. (Anand, 2007) Two core strengths of using this approach focus on the goals of IPA in centering subjects' perceptions of their experiences, and how they make meaning from them. As such, the approach can be applied to an experience or collection of experiences within a learning game, and how players assemble components of that experience and their perception of actions and events within the game state, to make sense of it.

The first core strength of the IPA approach in this work is that IPA is an ideal approach to understanding a person’s experience, and how they assemble elements of the experience to create meaning. Smith & Osborn note that IPA examines the “life world” of a subject and (i) “attempts to explore

personal experience”, and (ii), is concerned with “an individual’s personal perception of an object or event”. (p.53). This approach leaves aside any effort to create an objective account of an experience or event and concerns itself first with the subjective interpretation of the user. To achieve this, researchers set aside their preconceptions and pre-understanding of the phenomenon being studied in a process called “bracketing” and try to understand the subjective interpretation of the participant.

The second core strength of using an IPA approach to understanding game-based learning in game systems is its focus on understanding the process by which subjects make meaning from their experiences. This includes complex experiences involving processes, as Smith & Osborn (2012) note “IPA is especially useful when one is concerned with complexity, process or novelty” (p.55) Engaging in a complex simulation modeled within a game, the processes within it, and the subsequent player processes of meaning making are well supported by using an IPA approach.

Research Design Details

Sample and Recruitment

A purposive sample of 12 middle school students was used as the subjects for this research. This sample size was an estimate of how many subjects will be necessary to reach data saturation and provide a breadth of experiences across the demographics represented in the study. Data collection in IPA is typically conducted with a relatively small sample compared to other types of research, given the amount of data and level of analysis that must be conducted on the transcripts for each subject. Research using IPA to address game play from the literature review varies between 6 subjects (Nixon et. al., 2012) and 14 subjects (Eng, 2017). An assumption of this study is that the focus on a specific game represents narrower phenomena than other phenomena explored with IPA both within and outside of game-based learning. As a result, the design assumes deeper analysis on a narrower range of outcomes.

The sample was assembled to represent a range of ages, genders, ethnicities, backgrounds, and experience with playing video games. Learners between the ages of 11 and 14 years were considered for the study, and roughly an equal number of boys and girls were sought within the gender mix, though girls ended up outnumbering boys. Participants with a range of video game experience were recruited, and all

participants sought were students enrolled in public schools. Table 1 below shows the planned ideal sample in tabular form, and recruitment efforts sought to match this target as much as practical. In addition to the details listed in this table, ethnicity and gender were carefully considered across the subject pool, with the goal of including a range of ethnicities and at least one or two non-cisgendered students. Two trans students are included in the sample. At the outset of recruitment, a minimum of 10 participants were sought as reflected in table 5 but included the possibility of including up to 15 participants, especially as doing so would have advanced the breadth of subject backgrounds and experiences, potentially widening types of observations. At the end of the recruitment phase, 12 players were ultimately selected, resulting in the sample.

Subject Number	Pseudonym	Age	Grade	Gender	Game Engagement
1	A	12 or 13	7	F	Light
2	B	12 or 13	7	M	Light
3	C	11 or 12	6	F	Moderate
4	E	11 or 12	6	M	Moderate
5	F	12 or 13	7	F	Moderate
6	G	12 or 13	9	M	Moderate
7	H	13 or 14	8	F	Moderate
8	I	13 or 14	8	M	Moderate
9	J	13 or 14	8	F	Heavy
10	K	13 or 14	10	M	Heavy

Table 1. Original target recruitment table.

To locate subjects, a recruitment survey was administered to several middle school parent teacher groups in school districts North of Seattle, WA, with the assistance of a local school board member. The survey was addressed to and completed by parents who thought they had children who

might have been interested in participating in the study, and the introduction to the survey interest form specified the criteria for inclusion (Appendix A). Children who are familiar with the game *Oxygen not Included* were not eligible to participate. The recruitment survey contained questions relevant to the criteria for building the purposive sample and contained questions to help characterize participant video game familiarity and habits. Specifically, players were categorized as “light”, “moderate”, or “heavy” game players depending on typical weekly engagement with games reported in the survey. Finally, the survey asked parents questions about estimated student comfort and ability in conversing with an adult in a research setting. This “Recruitment Survey” instrument is available in Appendix A. The results of this recruitment survey served as the basis to offer subjects an opportunity to participate in the study as the sample was assembled.

This study unavoidably took place during the COVID-19 pandemic, which is part of the context of this study. This impacted inclusion criteria and interview methods. For eligibility to be included in the study, students needed to meet the following criteria: 1. they must be in 6th through 10th grade; 2. they must be between the ages of 11 and 15, 3. They must have had sufficient physical and mental ability to independently play *Oxygen not Included* on a personal computer, 4. possessed the ability to understand the interviewer’s spoken English, and verbally communicate in English. From a practical standpoint, inclusion criteria also included 5. access to a personal computer with sufficient technical specifications to install and run the game, 6. ability to install and simultaneously run a video chat program with screen sharing ability, such as Zoom or Discord, 7. A stable internet connection, 8. willingness to provide consent (and parent consent) to be recorded during play, and 9. willingness to commit the necessary time to the study. The impact of COVID-19 and social distancing made online data collection necessary, hence the inclusion criteria of access to appropriate technology. While not a requirement for inclusion, four learners known to the researcher were prioritized, as they were likely to provide richer dialogue with the researcher. Criteria requiring exclusion from the study are: 1. Lack of access to necessary technology, 2. inability to communicate in spoken English, 3. previous play experience with *Oxygen not Included*, any other corollary stemming from the inclusion criteria.

Purposive samples are not intended to reflect the general public, and as such the rate of trends, themes, and behaviors observed in this sample are not generalizable to the greater middle school

population. Each case in IPA is analyzed in great depth on its own, independent of other cases and researcher pre-understanding, and synthesized into broader superordinate and subordinate themes only after the analysis. A range of behaviors emerged and were discussed, but this study does not seek to generalize the rate these themes might be expressed among the broader middle school population.

Setting and Data Collection

As much as possible, research sessions took place in a secluded, quiet setting free of distractions. This work is currently impacted by the COVID-19 pandemic of 2019, and all interviews took place over web meeting software such as Zoom, which enables both dialogue and gameplay screen recording. Session lengths were limited to two hours, and some participants engaged in multiple play sessions.

Once participants were chosen, they (and their caregivers) were provided with options for “blocks” of time they could sign up for, and coordination took place using a spreadsheet and e-mail. To provide buffer time, blocks of time were set at three hours even though data collection is limited to two hours per session. A wide range of times were available for participants. Session blocks were available at all times from 10:00AM to 10:00PM every other Saturday (beginning December 19th), every Sunday 9:00AM to 10:00PM (beginning December 13th), and every Monday or Tuesday from 12:00PM to 10:00PM. For families that required a different time, this was arranged on a case-by-case basis. A link was provided to participants to join the call, at which time the session was recorded and managed as described in the interview plans below. This pattern was maintained long enough to accommodate all participants, and long enough to collect sufficient data to address the research questions.

Interviews

Two semi-structured interviews were conducted as part of the data collection process, including a pre-gameplay interview and a post-gameplay interview. Smith & Osborn (2004) note that semi-structured interviews are the “exemplary method” for IPA due to their flexibility, as initial questions can be modified in light of participant responses, and interesting areas that arise can be probed further. (p.54) Mujtahid et.al. (2014) also notes, “the goal of a semi-structured interview is to “foster an environment where the

ideas and meanings conveyed by informants could be developed and further discussed in order to achieve a deeper understanding of the phenomenon under investigation” (p.87) And Eatough and Smith (2017) describe the real time interaction within interviews as providing “major flexibility” for the researcher facilitating an experience for a subject (p.29).

The pre-gameplay interview was designed to collect information about how the participant understands game play, and to establish some insight into the way the subject understands the domain knowledge represented in the game in a general sense. The pre-gameplay interview instrument is included as Appendix B and consists of guiding questions that will be expanded upon with follow up questions as necessary. While the most essential data pertaining to the research question will be generated during the think-aloud activity, the pre-interview provided critical background information for understanding the player’s previous experience with games, games and learning, problem solving in game spaces, and meaning making in games in a general sense. The data are also evidence of existing player strategies for problem solving in game spaces, and subject to analysis within IPA. Pre-interviews were transcribed and served as the first source of interview data.

The post-gameplay interviews were conducted at the conclusion of subject gameplay and served two purposes. First, this interview included a series of guiding questions that focused on the overall player experience within the game space. While most of the data in this study was obtained from think-aloud recordings during gameplay, as Charters (2003) notes, any shortfall in the think-aloud results may also be supplemented by other sources of data gathering such as semi-structured interviews. This was very much the case, and post-play interviews provided far more clarifying thoughts on player thinking than pre-play interviews. The post-play interview served as an opportunity to fill in shortcomings and gaps in the think-aloud data, such as asking about specific critical incidents, or clarification of earlier statements. Charters also notes that along with observation, post-engagement or “exit interviews” serve as excellent vertices for triangulation, reflecting on material collected during a think-aloud activity.

Think-Aloud Game Play

Think-aloud interviews concurrent with gameplay sessions provided the core method in this work for collecting data on how players make sense of gameplay. Think-aloud protocol, interviews, or “think-

alouds”, are a data collection activity that relies on the informant continuously speaking out loud while engaged in some activity or intervention, in order to provide information on what they are thinking about, and why they are taking specific actions. (Van Someren et. al., 1994) This method is useful for a dynamic activity with evolving thoughts, as it provides “direct data on the ongoing thinking processes” (Someren et. al. 1994), and they serve as a means to “map out the actual mechanics of human thought processes” (Charters, 2003, p.68) Think-aloud protocol and interviewing has been used extensively in several domains such as human centered design and engineering (e.g. Robinson et. al., 2015), language studies (e.g. Schellings et. al, 2006), and is a popular method for researching product and protocol usability (e.g. Martin, 2007). Think-aloud protocol shares several characteristics with semi-structured interviewing that lends itself to IPA, such as real time data collection (Eatough & Smith, 2017), the ability to prompt and adjust prompts (Smith & Osborn, 2004), and the ability to ask for clarification (Chambers, 2003). Appendix C includes a list of such prompts frequently used during sessions.

Think-aloud interviewing is also an established method in learning research for probing for deep thinking and higher order reasoning and learning research. Indeed, Olson et. al. concluded in 1984 that think-aloud techniques are one of the most effective ways of assessing higher level thinking processes, and Reinhart et. al. (2019) also claims that think-alouds provide “unprecedented insight into student thinking”. (p.1) They also describe think-aloud interviews as providing insight into exactly how learners approach questions, reveal their reasoning, as well as determine if questions are interpreted as intended. (p.1).

Researchers are also increasingly using think-aloud interviewing for hermeneutic phenomenological research, including phenomenological research applications to learning questions. For instance, Lauterbach (2018). Lauterbach notes that a strength of this approach is that going beyond semi-structured interviews into other formats with participants helps new meaning emerge and promotes increased understanding of the phenomena. Think-aloud interview techniques are well suited to IPA research specifically. As Chambers (2003) observes, in think-aloud interviewing participants are treated as quasi-researchers, it serves as a basis for rich description, and emphasizes methods of interpretation for making best use of the data, which are all core requirements of an IPA approach.

An introduction, instructions, and a set of guiding principles and core thought prompts were used as the instrument for the think aloud exercise, and is included in Appendix C. This includes a series of prompts that the researcher drew from to elicit thoughts from players at key times if players lagged in dialogue or their talking otherwise dropped off. The prompts were also often used to link a thought process to a specific action occurring on the screen. Examples include “why did you just [observed action]?”, “how did you decide to do what you just did?”, “what were you thinking as [observed action]?”, and “what does that mean to you?”. These examples are closely tied to the game elements and will in many or most cases be subsequently linked with the game model and form. Other questions in the instrument are designed to probe for behaviors and thoughts that don’t necessarily evince themselves through observation, might not present as immediate thoughts, and are not necessarily linked to game actions and components. Examples of these types of questions include “what are you looking at?”, “what are you thinking about?”, and “what is your strategy here?”.

The game play screen for each think aloud session was recorded alongside an audio recording of the participant thinking aloud. In addition, the researcher took notes on player behaviors and dialogue throughout the activity, to add to the data (entered into NVIVO 12 as notes), and importantly, to serve as part of the basis for post-play interviewing. Collectively, the recordings and notes served as the data source for each session. Post-play interviews immediately followed think-aloud game play sessions.

Data Management

All data were collected and stored in a secure cloud drive on the web for security and preservation. A digital notebook logged metadata associated with each data source, including subject, date and location of acquisition, interview length, and notes relevant to subject instructions and data collection. All interviews were transcribed into text using a YouTube feature, or by the researcher.

The qualitative data analysis software package NVIVO 12 was used as the primary tool for conducting data analysis, and also served as a data management tool. All data files were loaded into a dedicated NVIVO 12 project, and an updated copy of the project file was updated after each working session and uploaded to the project repository on the cloud drive for security and preservation. The NVIVO 12 system embeds all associated data files in its file structure for use in coding and analysis,

individually referred to as “sources”. The software facilitates data file management, and serves a means of categorizing, opening, reviewing, annotating, and coding files. NVIVO 12 can read many file types, including .pdf and word documents, spreadsheets, images, audio and video files, and provides tools for analyzing them. The software also provided a means to code and transcribe audio and video content directly with use of timestamp and selection tools, and tools for coding locations on images and in videos. Most data analysis took place directly in NVIVO using this system. Using NVIVO 12 effectively kept all materials for data and analysis in one secure file.

Data Analysis Plan

After data were collected and organized in NVIVO 12 software, analysis began using the IPA approach to analysis as articulated and refined by Smith et. al. (1993), Smith & Osborn (2003), and Eatough & Smith (2008). Smith & Osborn (2003) begin with the assumption that by using IPA the researcher wants to learn something about the subject’s psychological world, which “may be in the form of beliefs and constructs that are made manifest or suggested by the respondent’s talk” (p.66), and as Eatough & Smith (2017) state, the researcher wants to “mine” the material for meanings. (p.13) They describe how data analysis is conducted through an interpretive hermeneutic process to achieve this goal in an effort to answer research questions and outline the steps of analysis of IPA data. Importantly, through the process of “bracketing”, the researcher sets aside their preconceived ideas, assumptions, pre-understanding, and paradigmatic lenses, allowing participant understanding of a phenomenon to exist on its own terms. Behal (2019) articulated a six-stage model for IPA data analysis inclusive of all steps outlined by several of Smith’s works, which was used to guide analysis in this work, presented as table 2 below.

Behal has taken previous expressions of the existing process for IPA analysis, and articulated stages with a stage task (goal) and a concise process to achieve that goal. It includes all the steps articulated by Smith & Osborn (2009) and Smith et. al. (2009). The process begins with all data from the first subject, from all four instruments in this study. Stage I of analysis is the task of listing words, phrases, and ideas in the first transcript, and creating a set of “raw data” with the phenomenon in mind. Stage II involves linking specific phrases and examples from the raw data to emergent themes and identifying themes and patterns in the data of the first transcript. In this stage, the researcher will link specific

phrases to themes that most closely capture the essence of the phenomena. In stage III, the researcher engaged with member checking with each participant, to ensure recorded statements and meanings are consistent with the participant's experience. Also in Stage III, the researcher will label the emergent themes from stage II, detached from concern about any relationships between them. This process parallels elemental coding methods used in qualitative analysis (Saldana, 2016), specifically encompassing descriptive coding, concept coding, process coding, and especially in vivo coding as it prioritizes and honors the respondents voice, which is critical in IPA.

Stage	Task	Process
Stage I	Notation of Words and Ideas	List words, phrases, ideas, convergent patterns, and build raw data from transcript with phenomenon in mind
Stage II	Review Data for Emergent Themes and Patterns	Review raw data, identify themes and patterns, use specific phrases that capture essence of the phenomenon
Stage III	Member Checking, Code One Interview	Execute member checking. Code an initial interview, list emergent themes from Stage II setting aside relationships between themes
Stage IV	Cluster Themes from Interview	Cluster while avoiding redundancy and repetition, include verbatim quotes
Stage V	Classify Themes	Themes will be grouped and classified as "superordinate" or "subordinate"
Stage VI	Repeat for Each Interview	After Stage I through V are completed for each interview, roll up all results into a master list

1.1 <i>Subtheme 1</i>	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1.2 <i>Subtheme 2</i>	Yes	Yes	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
1.3 <i>Subtheme 3</i>	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	No	Yes
2. Superordinate Theme 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2.1 <i>Subtheme 1</i>	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
2.2 <i>Subtheme 2</i>	Yes	No	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes
2.3 <i>Subtheme 3</i>	Yes	No	No	Yes	Yes	No	Yes	No	No	No	Yes	No	Yes	No	No
Etc.															

Table 3. Pre-planned Table of Themes, example

Reliability and Validity

Care was taken during the data collection and analysis process to ensure that data was accurate, valid, and reliable. Creswell (2002) notes several verification strategies that can be used to validate findings and increase reliability of the data analysis. These are participant integrity, triangulation, and data corroboration. Participant integrity was partly managed by careful selection of subjects based on data from the recruitment survey, ensuring participants are not biased by having played the game, and meet criteria for inclusion. The survey includes a question on trustworthiness of the participant, and the pre-interview includes a question about the players ability to continue with play tasks even if they feel “stuck”.

Think aloud instruction carefully noted that only questions about the basic functioning of the game or technical issues will be addressed by the researcher, and players will be redirected to the task if external help or insights about the game are sought. Data in the study was triangulated between multiple data collection methods. Most significantly, the post-play interview was an explicit opportunity to seek insights into critical moments during the think-aloud interview, to ensure proper understanding by the researcher. Post-play questions also addressed responses and thoughts in the pre-interview, or even survey responses, acting as “exit interview” questions for triangulation described by Charters (2003). This provided the researcher the opportunity to approach critical incidents, questions, observations, or other

information observed in the think-aloud from another angle, and gain confidence in player intent and understanding.

Data was corroborated or subject checked in three ways, to eliminate threats to validity of interpretation and results. To corroborate data, all participants were provided copies of all data they provided for the study, and transcripts of the interviews. Participants were asked to review their data for any information they believed was inaccurate. Ultimately, no participant expressed concern about the accuracy of the transcripts or information they were provided. Additionally, toward the end of data analysis participants were provided with a shorter “highlight sheet” representing some of the most relevant and quoted examples from their data, as a final point of data corroboration on some of the more critical points. Again, no participants expressed concern when provided the information and quotes that are presented in the analysis. Finally, coded data were checked by a second reviewer experienced with game-based learning as a reliability check. To achieve this, the NVIVO file was provided to the second reviewer, who will then scan all the coding in the interviews, and each play session. Any discrepancies, disagreements, or uncertainty were flagged and discussed with the reviewer, and then resolved by consensus. There were four instances for which conversation emerged, and they were quickly resolved. The reviewer was compensated for their time.

Ethical Considerations

Ethical considerations were seriously considered for this research project, and, and University of Washington Institutional Review Board (IRB) approval was obtained for this study. No major ethical concerns were noted for the major intervention, the gameplay sessions, nor administration of any of the data collection instruments involved. Of most ethical significance is the involvement of minors between the ages of 11 and 15, considered a vulnerable population. Supplemental forms pertaining to this population were filed along with the primary IRB application, and IRB was approved. The study requires no physical intervention, does not work with sensitive psychological topics, and was unlikely to result in discomfort to subjects. Participation in the study was completely anonymous, and the identities of participants were protected using pseudonyms in analysis. The researcher read the consent form to each

participant and ensured that they understood they could cease participation at any time, and that they understood their identity would be protected. Consent was obtained for all recordings. All recordings, data, and analysis were secured in a password protected computer and cloud drive. There were low risks for harm or consequences in the case of a data breach. Play sessions were capped at two hours, to reduce any sort of fatigue on the subject.

Chapter 4: Dissertation Results

This chapter presents the results of the method as described in Chapter 3: Methods.

Data and Gameplay Characterization

The twelve participants outlined in table 4 participated in the research process, and contributed data via think aloud gameplay interviews, and summative interviews. Most players participated in one play session, but two players contributed an additional second play session (Hiram and Bran), and two players contributed a third (Fern and Celeste). The total time players engaged in gameplay ranged from 46 minutes to 241 minutes, and in aggregate the total data set included 1,274 minutes of game play (21.2 hours). A basic overview of participant play experience is presented below as table 4. All gameplay videos were divided into 15-minute segments using Cyberlink Power Director video editing software, to make file sizes manageable and analysis easier. All data were then loaded into the qualitative software package NVIVO 11 for coding, quote transcription, and annotation.

Participant	Age	Gender	Experience Level	Play Time (min)
Axel	12	M	Some Experience	65

Bran	12	M	Some Experience	166
Celeste	11	F	Some Experience	182
Darren	13	M	Some Experience	77
Emery	12	F	Little to No Experience	54
Fern	12	F	Some Experience	241
Greta	14	F	Some Experience	81
Hiram	15	M	A Lot of Experience	142
Isaac	13	M	A Lot of Experience	77
Jade	11	F	Little to No Experience	46
Kari	13	F	A Lot of Experience	86
Letty	12	F	Little to No Experience	57

Table 4. Participant Overview

The data was analyzed per the coding plan outlined in Chapter 3 and included four layers of detail. As game players took actions and exhibited behaviors in the game, these were described in NVIVO in text at the point they occur in the video, to convert game actions into codable text. This first set of descriptors was an extensive set of items describing behaviors such as interactions with game components and systems, to capture actions taking place in the game space, often using formal terms. This resulted in an expansive list of 534 action, behavior, and component terms items in the NVIVO inventory. These terms were organized into a two-tier hierarchy. For example, Overlay/Atmosphere, and Overlay/Power both pertain to the overlay system, but the second descriptors pertain to different system information overlays. This process was solely to make occurrences in the gameplay video easier to analyze and describe.

The analysis codes addressed the themes developed for the interpretative phenomenological analysis (research question 1). These codes were created at the level of IPA

thematic analysis, as each case was reviewed one at a time. Both description and coding density was significantly higher early during gameplay sessions as players began to explore the gameplay system and everything was new, and coding rate lowered and leveled off as gameplay sessions continued. As a result, the first 15-minute segment of play for each participant averaged 36 items (descriptors or codes) representing notable interactions with the game, with the final segment resulting in an average of 14 codes.

Each play session was unique, and the pace of player gameplay, as well as overall number of actions executed in the game varied widely by player. At minimum, each player accomplished five significant tasks- establishing a basic source of power, a source of oxygen, a source of water, a bathroom, and sleeping arrangements for characters, and each player survived at least three in-game days (“cycles”). These were the only gameplay commonalities between all players. Two players (Emery and Letty) accomplished only these tasks over the entire duration of their sessions, while every other player was able to delve deeper into one or more advanced systems in the game.

The IPA results for research question 1 are summarized in a table demonstrating superordinate and subordinate themes. Results addressing mental models (research question 2) are presented and described in terms of “critical incidents”. There is a close relationship between IPA results for interpretation and mental model results, as they are interrelated. As appropriate with the IPA approach, themes are supported with examples from the data in the results, adding a strong narrative component to the results. Similarly, typical critical incidents are used as examples to explain types of mental model shifts observed for research question 2, and a few examples are used in question 3. Several examples used to describe IPA themes in question 1 are used again in answering the second and third research questions about mental model shifts and game design recommendations, to connect examples across questions.

There is a tension in the IPA results between honoring participants’ genuine interpretation and think-aloud responses and acknowledging that there is an intended model

designed into the game that is sometimes aligned, and sometimes differs, from player interpretation. Conducting an IPA study requires bracketing and setting aside preconceptions and models about the “rightness” of what participants are saying, as well as setting aside theoretical frameworks such as experiential learning during the initial analysis. As a result, many examples and statements appear when exploring and describing interpretive themes without focusing on their accuracy or veracity as reflected in the real-world domain. For example, if a player makes a game decision provides a statement of reasoning based on an interpretation that plants “breathe oxygen”, this specific belief and basis for interpretation and actions are described, not whether the interpretation is “accurate”. Many of these examples are related to “critical incidents” in the mental model portion of results (R2), when attention is turned to focus on determining the extent to which a game can result in player mental model shifts. When these statements are revisited in the question addressing mental model shifts in the study (R2), the explicit goal is to note these interpretations, and whether the underlying player understanding and mental model changes through game consequences and outcomes.

The final codebook used in analysis for all research questions is presented below as Table 5.

Code	Description
Textual Interpretation	A player using any sort of text (numbers, words, symbols) on screen to interpret something
Guiding Text	Reading and using tutorials and alerts that appear on the screen
Tooltips	Reading bits of information by clicking or hovering a mouse over game components

Data Tables	Reviewing a table of data available within the game
Visual Interpretation	Using visual assets to make sense of the game state
Iconography	Using signs (icons, indices, and symbols) to interpret phenomena in the game
Graphical Form	Making inferences from component image assets in the game
Weighting Visual Phenomena	Assigning great weight to a visual phenomenon in interpretation
Real World Models	Using an existing mental model (or schema) of the real world to interpret something in the game
Game Mediated Interpretation	Interpreting things in the game through the lens of other games
General Gameplay Patterns	Interpreting things in the game from other general gameplay patterns and mechanics
Model from Other Game	Interpreting things in the game based on similar characteristics in other, specific games
Game Mediated Real World Phenomena	Interpreting a real-world concept in a game, based on how it is modeled in another game
Proximal Problem Interpretation	Interpreting a problem or challenge as caused by a nearby but unrelated component
Quantitative Aversion	Conspicuously avoiding available quantitative information that is immediately useful
Aligned	Player mental model or belief aligns with the real world, as understood by domain experts

Differs	Player mental model or belief differs with the real world, as understood by domain experts
Unknown	A player expresses uncertainty or lack of knowledge about a specific concept

Table 5. Analysis Codebook

R1: Interpretative Phenomenological Analysis Results

This section addresses the first research question of this dissertation, “what major themes of interpretation can be identified for youth meaning making of knowledge structures in games for learning?” During analysis, four superordinate themes of interpretation emerged from the data, capturing how players interpreted the game space and made sense of it. These superordinate themes are textual interpretation, visual interpretation, real world models, and game mediated interpretation. These four themes capture how players made sense of what was taking place in the environment. The themes are listed in order from most literal type of interpretation, to most abstract. Each of these themes also exhibits two to four subordinate themes. In addition to these interpretative themes, two additional patterns are described as supplementary findings, “proximal problem interpretation”, and “quantitative aversion”. The full list of superordinate and subordinate themes, along with which participants made meaning of game elements using these themes, is listed below in table 5. This section explains each of the themes and provides supporting examples from the data. Two supplementary themes that emerged during analysis are listed in table 6. These differ from interpretative themes in that they represent two patterns of interpretation, but do not speak directly to how a player interprets something specific in the game space.

Theme	Axel	Bran	Celeste	Darren	Emery	Fern	Greta	Hiram	Isaac	Jade	Kari	Letty
Textual Interpretation	x	x	x	x	x	x	x	x	x	x	x	x
Guiding Text	x	x	x	x	x	x	x	x	x		x	x
Tooltips	x	x	x	x		x	x	x	x	x	x	x
Data Tables	x	x	x			x	x	x	x	x	x	
Visual Interpretation	x	x	x	x	x	x	x	x	x	x	x	x
Iconography	x	x		x	x	x	x	x	x	x	x	x
Graphical Form	x	x	x	x	x	x	x	x	x		x	x
Weighting Visual Phenomena	x	x		x		x	x	x		x		
Real World Models	x	x	x	x	x	x	x	x	x	x	x	x
Game Mediated												
Interpretation	x	x	x	x	x	x	x	x	x	x	x	x
General Gameplay Patterns	x	x	x	x	x	x	x	x	x		x	
Model from Other Game		x	x	x		x		x	x	x	x	
Game Mediated Real World Phenomena		x	x				x		x			

Table 5. Interpretive Themes

Proximal Problem												
Interpretation	x	x		x	x	x	x	x	x	x	x	x
Quantitative Aversion	x	x	x	x	x	x	x	x	x		x	x

Table 6. Supplementary Themes

Textual Interpretation

The first superordinate theme to emerge is textual interpretation, which featured the subordinate themes of tooltips, guiding text, and data tables. Textual information represents words and numbers at various places within the game system that provide players information on what components and their attributes are, as well as how different systems work in the game. Oxygen not Included is rich in information, and is encoded in many layers, however the most explicit and fundamental source of information is on-screen text, providing a direct basis for player interpretation of many of the game components. These labels and instructions were intended to be unambiguous by the designers. Most of the time this appeared to be true, however player interactions and interpretations of some types of textual information were limited, and some players interpreted this information differently than the designers intended, shaping player understanding and actions in unexpected ways.

Guiding Text Interpretations

The first possible interaction players might have with textual information in the game of any type comes in the form of tutorials, which appear as lines on the top left portion of the screen. Tutorial text is not attached to, nor does it refer to any specific game component. Tutorials cover various gameplay topics from basic controls to component functions. They are generally short, ranging from a few sentences to a paragraph in length, and are written in plain, direct language focusing on one narrow topic. Reading tutorials is not required. Nine players engaged with a tutorial at least once. For instance, several players such as Axel and Bran highlighted and read text about controls out loud as they began exploring the game. Some players that engaged with tutorial text did so early on, such as Axel, Celeste and Isaac as they

learned about controls and basic colony requirements. Greta said, "I'm looking at the colony management tutorial, which I think I should look at first". Others such as Hiram did not do so until later in the play session, until at least 15 minutes had passed. In these cases, the action was preceded by some problem or uncertainty. For instance, when Hiram was uncertain about how to do certain tasks pertaining to water, he moved his cursor over to the tutorial list and read an item for the first time, and Fern also read tutorials on both polluted water, and fetching water. No participant read more than half of the tutorial items available, and three participants (Emery and Jade) didn't engage with any tutorial items at all during the entire play session.

Player interpretation of tutorial text was universally straightforward, as tutorial text is based on simple, plain language text about a narrow topic, and as such players almost always interpreted text at face value based on the description. Sometimes players would attempt tutorial items immediately and comment on them, such as when Bran said "oh, that's cool" when he interpreted the text for game play speed variation and then immediately pressed buttons to change the gameplay speed, or when Greta read the germs tutorial and immediately went to seek the germ overlay. While most tutorial text is short and simple, there were still some minor individual variances in interpretation. For instance, as Bran read a tutorial about game controls out loud, he spoke the letters "WASD" as a word, as many experienced game players do, and immediately interpreted it as being identical to the common gaming keyboard control scheme.

Another form of guiding text provided to players is "alert text", which like tutorial text, is detached from specific game components, and appears on the UI on the top left of the screen co-located with the tutorial items. These statements refer to something about the overall game state, and these one-line notes are designed to bring player attention to critical matters. Examples include "no outhouse built", "insufficient oxygen generation", and "no food source". These alert texts are typically just a few words long, and represent a reference to a critical matter in the game state that players may wish to address. There were many examples from gameplay data.

With regard to player interpretation, alert text is one step removed from tutorial text, in that it represents a direct statement about the overall game state, but provides only short sentences with no additional context, and unlike tutorials provides no explicit directions or solution. Players typically understood the immediate challenge or need expressed by an alert text. For instance, Greta interpreted “no oxygen generator built”, repeated the phrase out loud, and stated “okay” while mousing over to the oxygen generator build command, and reviewed the requirements. And Celeste, on seeing the “no outhouse built” button, went into the build menu to see how to build one. There were exceptions, such as when Letty observed within the first minute of her session “the exclamation points where it says no oxygen generator”, but had trouble understanding what that meant, and what to do in the context of the game. She scrolled through the play space and explored for a long time before moving forward with other actions, effectively ignoring the alert.

A few players, while technically having engaged with one or more tutorials or alert texts, did not seem to pay them much heed or follow their advice. For instance, around fifteen minutes into his second playthrough, Darren had cleared most of his tutorial actions without looking at them and had five alert texts at the top left of the screen as he became very flustered, loudly saying “it doesn’t say what I need to do!”. When asked about this, he said he wanted to be explicitly told what to do next in the game. Emery also expressed “I am not sure what to do”, even as four tutorial items and three alert text items were present and uninspected at the top of the screen. A few players such as Hiram interacted with the guiding text just a few times and ignored it for the rest of the game. Toward the end of his session, Hiram had three lingering alerts and eleven unviewed tutorials on the screen.



Figure 4. Hiram playing, with numerous alert texts and tutorials that have been ignored in the top left of the screen, and a tooltip over a space with oxygen.

While most player interpretations of alert text were narrow and literal, in a few instances players inferred things about the game. For example, when seeing the alert text “made a mess”, Letty inferred it impacted the smell, “it smells really bad because it said made a mess in the corner”, When players did notice and respond to alert text, they often varied in their approach to addressing the alerts based on their understanding of how best to address the issue.

Tooltips

The next level of textual information available to players in the game comes in the form of tooltips, which are immediately accessible bits of information players can read by clicking or hovering a mouse over game components. This text reveals at minimum the name of the game component the player is hovering over and its temperature, and often other attributes of the component, such as the material it is made of or its mass, among others. Many component tooltips reveal some manner of categorization or classification, such as “mafic rock”, or “consumable ore”, which are attributes of components that affect it. Like other textual information, tooltip information is short, narrow, and explicit. However, players exhibited a much

wider range of interpretations based on information in this form of text than that in the tutorial text or data tables.

All players at least observed the presence of tooltips, and almost all of them used tooltips to interpret components and the environment. Emery was the exception in that she did not pay attention to or use tooltips, relying instead almost exclusively on visual cues. Most players simply used them when they wanted to know what something was, such as Jade hovering over a chamber of gas to note that it is filled with carbon dioxide, or Kari hovering her mouse over a green component she suspected was algae, to confirm it. Players focused mostly on the name of an object, but sometimes looked at additional information such as its material or other attributes in the tooltip. Most players never commented on any of the quantitative information in tooltips such as temperature, pressure, or power loads.

Player interpretation of tooltip text and terms was based on an individual's understanding of the information, and their own models. For instance, when seeking food Bran observed that tooltip over the mineral oxylite read "consumable ore", and he interpreted it to be edible stating, "you see this... this here is a consumable ore", and thought it was a food source. When asked for clarification on what that meant, Bran stated "you can eat it". Axel and Celeste drew the same conclusion from the same term. Other players that hit upon that label and commented on it had a different understanding, for instance Darren said "Consumable ore. That means like that... ore that you can use for stuff. I don't exactly know, but something like that."

Player interpretation of tooltip meaning frequently went beyond the narrow text presents, and players inferred additional ideas beyond the immediate narrow concept. For instance, Isaac hovered over a plant where the tooltip read "harvest ready" and said "it looks like I can eat them... my little dudes can eat them". This particular plant happened to be edible, but not all harvestable plants in the game are.

Sometimes players did not know the meaning of a term in a tooltip, or their internal definition of the word was not aligned with what the designers intended. When Darren saw the

hypothermia condition applied to one of his characters, he said “hypothermia... I don't know what that is”. Fern said the same thing, “I see that they have something called hypothermia. And my first guess is that they don't have enough oxygen”. Much later on, as the problem persisted, Fern temporarily left the game to look up the definition of hypothermia using Google and revised her understanding. Fern also didn't know the meaning of “idle”, “excavating”, “barracks”, and “pneumatic”, and guessed at what they meant, but did not look up the definition of any of these additional words during play. And extending a prior example, when Bran saw that algae was categorized as “organic”, he therefore declared it was also “consumable”, even though it did not have that tooltip classification, and not all organic materials in the game can be eaten.

Some player guesses at definitions were noteworthy as well. For example, at one point Fern noted one of the characters was labeled as “idle”, and stated “what does idle mean? I don't know... it says it on Discord too. I don't know. I mean it's in red so it's maybe something bad.” In fact, about an hour later the word came up again when a power generator was idle, “Generator idle. What does idle mean? I think it means “not there”. In another example, Bran noticed that a particular component was labeled “sedimentary rock” and said “sedimentary rock is like a fraction of rock... a whole rock. I think.” Several times, players also came away with a definition for a word they didn't know based on some other information in the game. For example, as Jade explored information in the game she believed was associated with pneumatic doors in the game, and wondered, “what does pneumatic mean?”, and eventually came upon extra textual information leading her to state “oh, encloses areas without blocking gas flow”, thinking this was the definition.

Unknown or differing definitions were by far the exception as players interpreted what tooltip information meant, however tooltips were not always enough for players to completely understand the component. For instance, Axel saw a number in a tooltip on a unit of gas in a chamber that represented atmospheric pressure, but interpreted it as mass of air, “how much oxygen is in there”. He stated, “I think it's running out of oxygen, ooooh that's not good. Cuz it's

becoming breathable and barely breathable, and the number is going down. Because the grams of oxygen”. The number he referred to was in fact atmospheric pressure, which was in fact slightly lower than the area with the oxygen diffuser but was nonetheless full of oxygen and stable.

In another common example, several players such as Kari, Jade, and Greta had trouble figuring out why characters were not storing materials in storage containers. Greta was unaware her workers had built it out of some sandstone she had already mined, and when she hovered her mouse over the container the tooltip listed (among other information) the material it was made of, and the fact no filters had been designated by the player establishing what things characters could store in the bin. The tooltip indicating that the bin was made of sandstone added to the confusion, “I’m looking for a way to... filters not designated, is that... sandstone. Well, it says... I’m assuming I have to get it because it doesn’t say any other material. I guess I’ll just get some and see if that works.” She proceeded to mine more sandstone, which did not fix the problem. About ten minutes later in the game, Greta returned to the issue, “The storage is still not working, I guess I can try and build another one. I don’t actually know why storage needs filters”. She wondered about filters thinking they pertained to “like water or something”. Finally, she clicked on a filter menu and laughed at her prior interpretation, “Hahaha, well, that makes more sense”, and proceeded to set storage filters. Hiram was momentarily confused by this same mechanism, but very quickly figured it out through trial and error, “It says it has no filter, I’m not sure what that means. Oh, I found what it means...” Other players such as Emery, Fern, and Kari struggled with this tooltip as well.

Sometimes the game system mechanics also contributed to unusual interpretations of in game phenomena. In one case, the way the tooltip appeared to “cycle” due to behavior of the atmosphere components in the game led Celeste to believe carbon dioxide was being converted into oxygen (which was not the case). Celeste hovered the mouse pointer over some empty space near her a new oxygen generator, and noticed the tooltip was cycling between

“oxygen” and “carbon dioxide” back and forth in rapid sequence. This puzzled her, but eventually she concluded the carbon dioxide was changing, “it's like getting turned into oxygen”. This phenomenon was actually due to how gas components are programmed to move and behave, and the rapidly cycling tooltip directly contributed to Celeste's misaligned idea.

A final interpretive facet within the subtheme of using tooltips to understand game space pertained to classification, and the fact that many actions can be performed with any object from a specific class of materials. Some players such as Darren, Fern, and Kari made specific mention of classification terms in tooltips. Hiram spent the first minutes of the game exploring the classification of many materials in the environment. Darren even used the term explicitly, as he was panning around exploring various materials in the game he said, “Not that much stuff is that hard. Oh, I take that back. According to their classification. Hard, Very Hard”, and clarified he noticed that some materials are classified by their hardness. He responded to this label by avoiding some materials, saying “I'd rather not have workers chipping at a piece of rock for ages.” Fern also made explicit reference to some terms in tooltips, saying “I think there are different categories. Like there are raw minerals, metal, et cetera”.

Data Tables

Data tables were the final piece of textual information available to players in the game, and were used to some degree by some players, and not at all by several. Data tables differ from tooltips in that they need to be activated by clicking to be seen and contain vastly more information about systems and components. Two types of data tables are available to the player. Game state tables are available through specific links in the game's user interface and provide information about key aspects of the game state, while object tables provide much more in-depth information about individual components such as a material tile or a building. Game state tables track key information about the player's progress in the game, and the overall development and condition of the colony. Examples include “Vitals”, which shows character

stress and morale, nutrition, and overall health. The “Consumables” table shows various food and medicines players have available, and their nutritional value, as well as any food allergies characters have. And the “Colony Report” shows a daily log of colony inputs and outputs such as food generation, stress changes, disease status, and power and oxygen generation. Object tables appear when most components are clicked, and they bring up a table of data specific to that item. Some examples of data in object data tables are specific heat, thermal conductivity, melting point, capacity, contents, overheat temperature, among many others.

Player interactions with data tables available in the game were infrequent, tended to be short when they occurred, and they represent the least used form of textual interpretation. Many players did not attempt to make meaning of anything in the table or use them to make sense of the environment or game state. Other players used them from time to time. Examples of use include Jade examining the data table for the bristle blossom plant to see its growing requirements, Fern using them to examine character stress, and Isaac looking at the colony summary.

Fern, Isaac, and Kari all examined the character vitals data table at least once. Kari only used the table once to see if the characters had food. Isaac opened that table and stated, “I am going to try to check the vitals of these. It looks like they are doing fine right now. I was looking just to see if they had anything that could potentially kill them in the future that wouldn't show right now”. And in Fern's case, she stumbled across it by accident when trying to see what other “things” there were to click, “there's something I haven't tried to click, and I need to click everything. Now what's this, I don't even know what that says”. She then clicked the “Vitals” item in the UI and began looking at the character vitals data table that appeared. “Oh, maybe this changes who is more stressful maybe”? As elaborated upon further under the “weighting visual phenomena” superordinate theme, Fern did not process the quantitative information, and interpreted the table as presenting characters in order of their level of stress.

Sometimes player review of data tables was narrow and incomplete, as with Fern above. In another case Celeste missed some information in a data table but assumed some behavior of a component instead. She was examining a coal generator in the build menu and was considering whether to build one, saying “It doesn’t emit heat. It just emits carbon dioxide. I think it does, but it doesn't say anything. It doesn't say it does”. She did later realize that this information was available in the data table, and after this she started examining the data table of a few other buildings to consider their behavior and effects.

When players did dig deeper into data tables, it was often because the data pertained to an area of particularly strong focus for that player in the game. For example, Celeste was very fixated on food production in the game, and ingredients and output of the microbe musher, and read all of the inputs and outputs of the machine, its power requirements, and physical characteristics. She read fragments of the table out loud as she read it “there's like a quantity of... the ingredient, dirt, and water, and calories”. Celeste also paid attention to data tables for requirements of various plants to grow from seed, and data tables on the planters she was building. Axel and Fern also explored the microbe musher this way.

Isaac engaged with data tables and associated component attribute information more extensively than any other player, attempting to understand the material, thermal, and operational properties of building types, and inferred several things from this information early on. “I'm paying attention to what I'll have to do with it, like what I'll have to do. Must be periodically emptied of polluted dirt. And then I am also looking at its effects, like what will happen. So, it has storage capacity, and then it has overheat temperature, so I'm probably going to have to pay attention to that. This will probably overheat it and do something bad to it, and that means that I won't have enough space, so I might have to build multiple”. These understandings, combined with his beliefs about how this kind of game should work (elaborated on further in the game mediated interpretation superordinate theme), influenced how he interpreted information.

Visual Interpretation

Visual interpretation was a second superordinate theme and encompassed player interpretations of graphical representations on the screen such as component art assets, animations, icons, and visual cues composed of these graphical elements. Like the textual interpretation superordinate theme, visual interpretation is dependent on a direct “reading” of the image or animation on the screen, albeit a reading of symbols, animations, and other images. Rather than reading and interpreting words to assign meaning to a particular in-game phenomenon or situation, players observe and interpret visual art and design to make sense of what is taking place or attempt to make sense of the visual asset itself. Like text, images and animations are explicit representations of concepts or ideas on-screen, however they represent one further step toward abstraction and are subject to a much broader range of interpretations among participants during play.

Three superordinate themes emerged within the visual interpretation superordinate themes, which were iconography, graphical form, and weighting visual phenomena.

Iconography

Iconography is a concept related to textual interpretation, and conceptually stands midway between written text and other forms of graphical content. A strict semiotic definition of icon is that it is a category of sign whose form indicates the object or concept being referred to. In computer programs in general, and video games specifically, icons are frequently used as simple graphical tools to refer to components, attributes, or other characteristics of the game state. *Oxygen not Included* uses dozens of icons as shorthand for various phenomena such as component attributes, environmental conditions, and character mood and feelings. Subjects in the study exhibited two interpretive behaviors with regard to icons, which are the meaning of the

icon, and the cause of the emergence of the icon. While icons and indices are intended to represent specific concepts in the game, there was some variation in player interpretation of the meaning of these signs, and sometimes players focused on one facet or both- the meaning of the sign, and the cause for its emergence.

Most instances of player interpretation of icons were based directly on the image of the icon or index. There were some icons that all players who commented on it interpreted to mean the same thing, such as Bran and four other players interpreting a light bulb appearing over a character's head as them having an idea. In another common example Axel noted a sign shaped like a turkey leg above a character and interpreted it to mean the character was hungry, stating, "so, how do I get food"? Similarly, Emery saw the same icon and said, "it looks like they are hungry", and Fern exclaimed, "Oh, they need food now!", when she saw it. Celeste actually referred to it as a sign, "they just looked hungry, the sign said", and proceeded to build a food generating microbe musher. A third common example was the toilet icon, which prompted Darren to state, "oh, we need an outhouse. They say they need one." when he saw it. When Hiram saw the toilet icon for the first time he said "that doesn't seem good. Looks like he has to go to the bathroom". And Kari said, "oh, I need a thing... I need an outhouse", and specifically referenced the toilet icon as the reason for this belief. Hiram noted, "That doesn't seem good. Looked like he has to go to the bathroom. I probably should put that outhouse down. It's not good to poop on the floor. This is a race against time." He lost. "Welp. Peed on the floor." Some player interpretations differed from the most common interpretation, such as when an icon appeared representing "no dirt" in an outhouse, Kari thought it meant "maybe like no plumbing or something", though a short while later only changed her interpretation when she used a tooltip.

While many players interpreted particular icons or indices as having a particular meaning, the cause was not always apparent, and the emergence of the icon led to other interpretations. A frequent example was the "snowflake" sign that appeared above cold

characters from time to time. Every participant that observed this snowflake sign interpreted this as an index meaning cold. For example, Jade saw this and stated, “Yes, I know you’re cold! It’s annoying and I can’t fix that”. Letty saw it and noted “It’s cold or something”, and Kari saw that sign, stating “It looks like they are cold, so I think I should do something about that when I build the generator”. Fern also believed her characters were cold, saying “they are acting like they are cold, but it doesn’t look like I can do anything that has to do with cold, so I think I am going to just have them make another room”. When Isaac saw this icon, he explained it in reverse “apparently they aren’t warm”. Regarding this specific index and interpretation, actions taken by players varied significantly, and some players focused on the characters, and some on the environment. Jade believed there was nothing she could do about the problem. Letty noted the problem, but never mentioned it again, and Kari went seeking a means of heating the environment.

Player meaning assigned to the emergence of the icon varied. Kari saw the same icon and set about trying to figure out why the characters were cold (it was largely because they were wet). After considering the problem for a short time, Kari interpreted the characters as being cold due to lack of sufficient oxygen. A second visual effect, related to the subordinate themes of graphical form and animations, actually reinforced this interpretation. A while after deciding her characters had insufficient oxygen, the screen turned dark, which Kari later said did not make sense to her at the time. Kari said there should be no difference between overall lighting deep inside an asteroid and did not initially think to attribute it to a day or night cycle. And indeed, this belief was later reinforced yet again by a third and different animation. One of the characters was snoring, and she thought this odd animation around it represented a lack of oxygen. And underscoring all of this, was the fact she saw “too much” carbon dioxide in her environment (though as with many other players, the level of carbon dioxide was quite fine). These graphical elements worked to reinforce Kari’s interpretation of the problem, leading her to seek solutions in a direction that ultimately did not work.

Another sign that was interpreted consistently between players, but engendered different beliefs about cause, was the red icon shaped like a power cord plug. When this icon appeared next to a device, many players (such as Bran, Greta, Hiram, and others) consistently interpreted it to mean the device had no power, though the interpretation as to the cause varied, even under similar circumstances, leading to different responses. Fern noticed the red plug symbol, prompting her to explore the power overlay, which led her to look up information on “producers” in the overlay diagram. Eventually she was led by another visual cue to her next interpretation and action, based on a diagram in the power overlay, saying, “so it said like the green thing is a producer... oh I need a manual generator!”, which she proceeded to build. Afterward, she noted that the term “producer” was not originally meaningful to her, but the image of the green line indicated it probably solved the “red power plug” problem and produced electricity. (Only visual information was used to solve this problem). Isaac believed this icon appeared because he needed more wiring, and Hiram once saw it and believed there was “not enough power for it” (he did not realize the circuit was wired wrong). He believed the circuit was complete, but that he needed to build more capacity (which was not the case).

Other red icons also attracted player attention, leading to various interpretations. For example, the “needs dirt” icon mentioned previously appeared for many players, indicating an outhouse needed to be supplied with dirt, shown by hovering the mouse over a red symbol that appeared under an outhouse when it was out of order. This led some players to understand what was lacking, while other players did not immediately figure out the meaning of the sign. When Letty completed building an outhouse, an “out of order” sign appeared on it immediately, because an outhouse is not supplied with dirt automatically. Letty noticed “the red thing under the outhouse”, and immediately decided it meant more plumbing was required, “like no thing to empty it out or whatever” and went seeking ways to attach pipes to the outhouse. Later on, as the icon persisted and her characters began to soil themselves, she clicked on the icon and realized she needed to fill it with dirt and proceed to go try and find some. In contrast, Isaac

realized it needed dirt, and acted immediately saying “I'm just going to start digging for dirt right now”.

Materials storage was the cause of much confusion for some players, and the icon was one source of this confusion. Greta issued a command to sweep a large volume of materials into storage, and noted that some containers for which she issued the command had a white broom icon over it, and others had a red broom icon over it, saying “so this stuff is still red, but the sandstone and dirt are all white”, and expressed confusion as to why it was different. And in an instance relating this “icon color change” behavior with icons with outhouse examples, Kari interpreted a supply problem with an outhouse as having been fixed as soon as the sign next to it disappeared. She had previously concluded that it needed more dirt, and was having trouble finding dirt, but once the sign disappeared, she stated “ok, it seems now, it seems like I have the dirt, I think they can maybe they can do it. The little icon thing is gone, so maybe it's ready”. These icons changing color also represent a form of “visual cue” that players often solely relied on for information, as described in the subordinate theme “graphical form” below.

Some players interpreted some indices more literally as icons. For instance, where Axel, Emery, and Fern all interpreted the turkey leg as an index meaning “food”, Bran interpreted it as actually representing chicken, stating “you want chicken? You aren't going to get any in this place”. Bran confirmed his belief the icon was indeed chicken in his follow up interview, thinking they might be introduced to the environment at some point. Similarly, Axel observed an icon of a ball and a “thumbs up” above one character that was conversing with another and asked “what is that little ball they are talking about?”, and “kept an eye out” for where it might emerge in the future.

Graphical Form

Graphical form was another subordinate theme, referring to players looking at component image assets in the game, and interpreting or inferring meaning from their specific visual rendering and

composition. The graphical form of material components in the game were frequently the basis of players interpreting their attributes or characteristics, and most players engaged in some type of this interpretation with only Jade not expressing such. For many aspects of the game, interpretation from visual cues was a dominant method players used to interpret phenomena, even when tooltips and data were available to give players very concrete attributes and characteristics of the phenomena.

Many visual interpretations were straightforward, and the data is rich with examples of players using the form of graphical components to draw conclusions from them. For example, Hiram completed a set of plumbing pipes, and clicked on the plumbing overlay to check that it was working, noting a line of blue circles inside of the pipes that were not there before, and stated “Hey look it's doing it! Awesome”. Several other players noticed their plumbing was working with the same visual information. Similarly, players often noticed their circuits closed or became functional not through tooltips or data tables from their circuit components, but rather when certain components such as batteries or transformers were “lit up”. This even occurred when characters completed circuits while players were not paying attention to them, as happened with Emery, when she was paying attention to a different area and then noticed later some components were “lit up”.

For some aspects of the game, the graphical form led to more player interpretation than text alone. The strongest example is the graphic rendering of atmospheric phenomena, the images of which led to far more player interpretation than text or any other information. Keri provided an example, saying “I think uh, well... there's kind of like a darker... because like, the oxygen has like blue particles, the carbon dioxide it's kind of like uh black, like a darker gas. Well, I think the color in the game, like you can see the difference, this is darker here, and also the carbon dioxide here... I think it's just to show us so we can see it. But see, there's also natural gas right here that's orange. And chlorine, it's also a different color”. Keri then went on to use gas color and quantity of color “patches” as the key way she interpreted atmosphere for the

rest of the game. In an example mentioned earlier, Hiram also made a note of gas colors, and interpreted the colors of the oxygen overlay as related, "It seems like they are doing something to the air... uh, well there's a yellow gas around it. Also, when you go to the oxygen overlay, it's just gray there". This gray area corresponded with liquid, which was gray on the overlay, but the main screen shows a layer of bright yellow gas just above that, and Hiram was uncertain as to whether they were one and the same, saying "I'm not sure if it is a liquid not taking up a whole tile, or what". The ambiguity of this boundary region and its graphical form prompted Hiram to communicate this uncertainty. Still, Hiram continues to rely on visual information to try to understand how gases were behaving for the remainder of the game.

In another example, Fern explored the oxygen overlay, "Oh... I imagine the red is where there is no oxygen. That seems to be kind of shifting. Maybe it's the opposite... no no no, I think the red is where there is oxygen. Because there is so little of it in these areas where there's like nothing. I don't think they would just put areas full of oxygen in the game. Because that would be too easy, and you wouldn't have to worry about oxygen." Note, that Fern did not use a tooltip to see what gas was in the area, and alongside attempting to understand it by color alone, Fern's belief about what a game designer might do reinforced her interpretation, a manifestation of the game mediated superordinate theme discussed later. This continued throughout play. Late in the game, Fern mined into a new chamber in the lowest part of her play area and noted only that it was unbreathable due to its color on the atmosphere overlay. She did not realize it was in fact chlorine gas emitted from local minerals, and breached the chamber, causing noxious chlorine gas to diffuse into her play area.

Axel and Celeste also interpreted the breathability of air by whether the sparkling animation they associated with oxygen was present. For example, in one case Axel stated "these blue particles in the background, I think that's oxygen, so that's really weird" when his character was struggling to breathe near the area. Notably, in this case he did not use tooltips or

click to see data on oxygen presence, or the overlay, but relied on the graphical representation of air. This was very common among players.

In other cases, exaggerated graphical form drew player attention, and led to interpretations of how the physics in the game behaved. A common example was the way the exaggerated meniscus of fluids was drawn, leading several players to conclude they represented a unique component. The way one of these gas-air boundaries was shaped led Greta to conclude that gasses were dissolved in the water, “when there's gasses in the water, I think that's what makes the bubbles.” This same exaggerated meniscus led Axel to conclude these bubbles were harvestable air nodes, stating “do I need to collect this, or do I need to just let it go out”? Bran also interpreted this as meaning there was oxygen inside the water, saying “ok- the oxygen bubbles... this is weird, there's giant bubbles and it makes the water look really weird, yeah because it has oxygen in it”. Celeste and Emery came to the same conclusion, all due to an exaggerated visual asset.

Another visual asset that led to particular interpretations was liquid bottles. Kari also observed how fluid jars were graphically rendered, which led her to believe her characters were not being efficient when cleaning up spills, stating “why don't they fill the jugs up all the way? That's kind of annoying”. All fluid containers appear to be only partially full as they are graphically rendered, but the volume they all contained was quite significant at 100kg. A tooltip and click would have revealed this, but the graphical representation of the component was the sole way Kari interpreted their volume. This was in fact true of almost all players.

In another case, Axel thought that a series of water pipes attached to a pitcher pump was a ladder, saying “oh what's that, is that like a ladder?” he later noted, “Wait no its a bunch of pipes in the water, so the water can come in, ok that makes more sense.” Greta also wondered at the graphical rendering of the pipes, “I don't know if having the pipes changes how much water it gets. I don't think it matters that much.” Hiram appeared to ignore the pipes and placed a pitcher pump on land above a chamber of water, with the pipes going only into dirt,

thinking it would reach. When it didn't work, he stated "I think I might have placed it wrong. It's not collecting any water." He tried something similar much later in the game, over a different chamber of water and grew flustered "It doesn't really seem like I did anything wrong here". He became so flustered, that when he built a research station, the first thing he moved into was plumbing. He proceeded to bypass the basic manual pitcher pump and submerged a water pump in the reservoir and began broadening his power system to accommodate it. Isaac didn't even go so far, and built a pitcher pump on a patch of ground with no water anywhere near it. He simply believed that building a pump would produce water, as in many games, simply producing a building will cause it to "create" the resource it is designed to manage. Soon after, he realized it needed to be physically connected to water, "It looks like this needs water, so I think I might actually move this".

Periodically, the graphical form of two objects adjacent to one another confused players. For example, Axel observed two pepper plants growing intertwined, and the way the graphics were rendered led him to conclude they grow on top of one another, saying "Oh they have linked another on top of each other to make it bigger. Also, it can't grow anymore." Eventually after discovering a tooltip showing "percent grown", Axel concluded they were still growing, albeit still on top of one another (which was not the case).

Players often interpreted some character graphics and animations as related to social phenomena taking place with that character. Some social concepts are modeled in the game, such as stress, morale, and duplicant relationships, and some character interactions within these areas generate signs or animations that players interpreted in a variety of ways. For instance, an earlier example noted Axel observed an icon of a ball above a character's head as it was conversing with another character, stating "what is that little ball they are talking about?", and he sought to assign deeper meaning to this interaction (the interaction actually has no fundamental meaning, other than characters are socializing).

As a common example, the graphical form of the characters in the game also led to some interpretations about their status or demeanor. Sometimes this led to perceptions of characters being unhappy or overworked, even when the characters were not. About six minutes into play, Darren said “they don't seem quite as happy now. Either there is something I have to get them to keep them happy, or the oxygen is going down like I thought.” (The oxygen level was fine). After about forty minutes of play, Fern observed the characters rendered in the same manner, and believed she had overworked them stating “they look like they are tired. I made them do a lot of work. I dunno, they also have those faces. They all look tired”. This led her to take an action to build massage tables, believing this may be a solution, “I was thinking a massage table wouldn't do much, but now that I think about it maybe it would”. Approximately twenty minutes later, Fern again interpreted two of her characters as being tired in a different scenario, which came about to fill her perceived need for an explanation as to why they were not helping to build another structure. Eventually Fern built a massage table thinking it would alleviate their bad back condition, “look at Burt, Burt has a sore back because of me. Probably because Burt has been working, but I did make a massage table”. The table does fix the bad back condition, but that condition is caused by sleeping on the floor, not being overworked. This idea of being “overworked” was frequently projected onto the characters, reinforced by the graphical form of how they were rendered.

Hiram drew similar conclusions about characters based on how they appeared on the screen. About forty minutes into game play, saying “It doesn't seem like they are very happy right now. Because of their expressions, but maybe it's always been that way and I just didn't notice”. Greta drew different conclusions as she observed their demeanor, “Everything has to at least be okay. Some of them are smiling. I mean this guy is holding his breath. I'm just looking at their face. They are not exactly smiling, but... see this guy, there's nothing wrong. This one is okay. So they all seem okay.” Bran interpreted one character's grimace as anger. And Bran interpreted a character, who had been running on the manual generator for a long time and was

drooling, as hungry and said “Oh god, I don't like that look. They are drooling, they need food!”. (The character was not hungry, this was just a comical animation).

Visual Cues

Several scenarios described thus far have also served as examples showing that many visual items in the game had graphical forms that served as visual cues for players, and players often came to rely on these cues more than other information. This occurred quite often, and some examples such as powered components “lighting up” have been discussed. Illustrating another common example, Fern noticed that the colors of certain building menu items changed when the player had access to the appropriate resources to build it. She used this to determine when she had finally mined the appropriate type of resources, noting when menus with buildable items shifted from gray to colored, “oh the base turned a certain color, yes, yes, yes, that's what I have to do”. Fern also noticed a short time later that dig icons change when characters can access them “oh I just noticed that when it turns kind of a white, a light white, when they can access it”. Fern began to use the visual cues of components changing colors as a primary means to understand when she had collected enough of the correct resources to create a building, when she didn't understand what specifically she needed. For example, in one case she stated “it popped up colorful.. it's all colorful now. At first it was all grey like the rest of this stuff. I think they got enough materials, I didn't see exactly what they did.” And ultimately, it was a visual cue that solved Fern's longest running conundrum and helped her realize copper was a metal. “I just realized they were mining a lot of copper, and suddenly it acted different”, referring to the build icon changing color when enough resources are available. Several other players began to rely on these cues as well. As one more example, building on the prior example of Kari initially thinking the outhouse needed plumbing, she also used icons to tell when enough resources had been collected, “it seems like I have the dirt, I think they can maybe use it. The little icon thing is gone, so maybe it's ready”.

In some cases, these visual attributes were what first drew player attention to them. One minute into his session, Axel said “I have no idea of where to dig, or what to dig so...”, and then noticed a copper ore component and stated, “these look shiny so...”, and began digging them. Axel did not immediately interpret the shiny ore to be copper. Similarly, Hiram noticed some cracked algae and stated “I was wondering why there's cracks in the algae. Maybe there's something in there. Oh yeah, it says buried object when you hover over it. Similarly, Kari observed some rubble around some objects, and then noticed the tooltip read “entombed”, leading her to interpret that rocks had somehow come to bury the building, stating “Entombed? Maybe I need to dig it out. Oh, I think that maybe somebody dug something up here and it fell down, or maybe rocks formed along it or something.” In this case, Kari began to seek an explanation for the unusual graphical rendering, highlighting one of many cases where players attempted to assign additional meaning to the specific way a graphical component was rendered”.

Some visual cues led players to make interpretations about what was taking place in the power and oxygen systems. A common building in the game, the oxygen generator, also created bubbles when fully operational, and many players used this animation to understand when their systems were working. Building on Fern’s scenario in the previous paragraph, when Fern got her oxygen generators up and running, she relied solely on a visual cue to tip her off that it was working, exclaiming “Yesss yes! It looks like the bubbles are the color of the very breathable. It should give off oxygen.” Similarly, Axel struggled to get a power system working, and when it finally began to function, he stated “yes power, much power, look the oxygen is coming, yes!” and proceeded to clap on seeing these bubbles and signs. Many other players used several types of systems as the basis for understanding systems. Power systems were also frequent examples, such as when Greta decided that her power storage system was finally fully working not through tooltips, the overlay, or other information systems, but when an animation began to emit sparks, “oh, I see sparks going through the battery!”

For a long period of play, Kari interpreted the animation of characters sleeping as stemming from a lack of oxygen. During the first night of gameplay, when they all lay down to sleep, Kari said “uh-oh, that seems bad. I think they probably need oxygen”. She then went looking through tools for “medicine” or something to revive the sleeping characters, eventually maneuvering into the oxygen utility construction menu. When they awoke in the morning, she interpreted this as being part of a game preventing her from losing. “Oh, it looks like they woke up and started mining. That’s weird. Maybe so I don’t lose?” This interpretation contributed to Kari choosing not to build many structures early in the game, “I’m not sure the little guys can do anything right now, because they are all oxygen deprived”. Axel expressed confusion when confronted with the same animation for the first time, asking, “why is everything turning gray”? but after seeing animations of his characters sleeping, he decided, “oh, they are sleeping”. On a related note, Fern’s characters actually were sleeping in an oxygen poor environment at one point, and waking up very tired, which Fern (correctly) assumed was due to them trying to sleep in poor oxygen.

The graphical form led to some curious interpretations. For instance, the iron ore component is rendered very similarly to the copper ore component, and as a metal includes the same reflective sheen. Fern gasped when she saw iron ore for the first time saying, “iron is copper... it looks like copper ore. It looks like it, from what I can see”. She previously struggled to identify metal ore in the game, overlooking copper, and then after this instance classified iron as copper. In another case, Darren interpreted a large swath of gray and black area a “big bad useless area”, when it was in fact a large chamber filled with fresh, clean water that appeared dull because it was on the edge of his sensor range, and he avoided this area for the entire game. The uncertainty of the gray area also concerned Hiram, “I guess might be able to go over here, but this part I can’t see here is disturbing. There might be something past there I don’t know, that may get in here and be bad.” Other players concluded blurred or grayed out areas as simply needing exploration, such as Greta “I’m assuming that if I expand it will light up like the

rest of this stuff, they can see what it is. I am assuming that I'm going to need some of this stuff.” And in one case of an unintentionally quirky form on screen, two components that lay over one another, a rock and a plant, each had a different classification tooltip. However, Kari thought it was one component with both tooltips applied to it, “it says ingenious (sp) rock, but it also says uproot. I wonder if it's like a plant and a rock?”

A couple of creatures in the game (which do not exist in the real world) had visual characteristics that players interpreted as meaning specific things. Kari observed a shine bug (a glowing creature) emitting light, and assumed it was warm based on how it looked, “I think maybe I could just have them dig through here and check out that little warm thing. I guess it's a glow bug.” When Darren saw a shine bug in a plant filled cavern, he opened the decor overlay to see the effects of these components. He said, “Do those little light things improve the decor? It looks like they do. The areas next to them are light green. Either that or they just live in the center where it is prettier. One of those.”

In a large number of instances players reacted to a developing issue only when graphical clues presented themselves. In a simple case, Axel first noticed his storage was getting full when a bar on the storage building was long enough to cause some red to appear at the end of the bar, stating, “eee that's a problem. It's almost full. Because this bar on the side, it's like red and yellow”. He had not monitored the storage at all previously. Many players followed this same pattern, and most were not aware of the storage capacity of this building until it was completely full, and it caused “red” to appear, or an icon appeared. Many times, other players didn't react until something broke. For example, Fern added an increasing number of power loads on one circuit, and despite the opportunity to examine the circuit strain in several ways, she only reacted when a wire melted and she saw her systems shut down, “wait they stopped... there's a wire acting funny there. What happened?”

Animations

Another subset of graphical forms that influenced player interpretation of the environment were animations. Most players interpreted most animations in the way the designers had intended, however, plenty of animations caused confusion. Initially, Bran observed the character “eating” animation and interpreted it as meaning the characters somehow conjured food or pulled it from the ground. “I put the mouse on the character, and it said eating a nutrient bar, and it's like oh, I thought they were just taking chunks of the ground and just eating them. When asked to elaborate further on where he thought characters got food, he thought the nature of the game meant they could simply conjure food, and early on believed that characters needing to access specific food items to eat them “wasn't part of the game”. When Hiram was replenishing an algae terrarium, he noticed the resupply animation and interpreted it as the algae growing. He said he was “not sure” why it grew. It turned out, he didn't notice the water delivery to the terrarium, and fixated on the animation of the terrarium being replenished. As was often the case for players, there were other information tools available to Hiram that would have provided extra information on what was taking place, but he did not use them.

As another example, Fern noticed within the first minutes of the game that there were oxygen bubbles coming from a tile near her character (it was oxygen emitting oxylite). She stated, “what are those bubbles, do they have trouble breathing?” About half a minute later after exploring some more, she again asked, “do they have oxygen right now?” and expressed concern that the bubbles might represent limited air. This animation also led Kari to believe for a short time at the beginning of the game, that she had started underwater “wow, there's bubbles coming out of there. Am I underwater? Can they breathe? Is there a surface or something I should try to get up to?” For several minutes Kari believed she may be underwater, but

eventually decided that the bubbles simply represent the oxylite emitting oxygen (which is indeed the case).

Another example is that players often first realized characters were suffocating due to a gasping animation. Bran even got annoyed at this animation, "I understand you're having trouble breathing, God Nisbett, you're hyperventilating, stop." Isaac observed a "coughing" animation that the characters did when they were on the edge of breathable air, and while building oxygen generators he stated "I'm probably going to have to build more of these, because I don't think they can breathe really well. They also start coughing when there".

In one instance, Letty believed that a character was stuck in the manual generator due to the associated animation. The animation featured the character running, as in a hamster wheel, and periodically falling down. This led Letty to believe the character was stuck inside. Bran observed the same animation, and when the character comically dismounted in similar fashion, this caused Bran to believe they had fainted, possibly due to a lack of oxygen. In another example of character animation interpretation, Fern's characters were building a structure, and due to the way the construction was animated Fern came to believe that her characters were all helping build a new building, stating "I think they are building different parts to it". This statement was made more relevant due to the fact a short time later she began to make particular interpretations to her characters not assisting on other buildings, such as them being tired or "maybe they are not good enough to make it". (The characters do not in fact build different parts of a building).

Several players observed the animation at the top of the screen that signals when the "day" and "night" cycle change, which features a stylized lightbulb in a metal casing, and several players struggled to understand what it was. This animation appeared when Kari's characters woke up, (when she thought they passed out due to lack of oxygen), saying "oh it looks like they got revived, okay. There was like a little thingy up here, and now they're all standing up. Probably just an aspect so that I don't end up losing." For a long while, she believed it was

some sort of resurrection device. During her first cycle, Letty saw it and said, "I don't know when they were sleeping, there was something up there". Other players interpreted it differently. Axel was confused about what this meant for a short while but came to believe it represented a "night" cycle. Darren immediately felt these clues meant it was night, saying "they're sleeping or something. And it's also darker."

Aside from the day/night animation at the top of the screen, in the top left of the screen an animated dial continuously spins, representing what point in the cycle it is. Fern observed that component and interpreted this as some sort of time keeping device. "Cycle 11. I think it's like a day, from what I can see if I understand the quote unquote clock right, it will either soon be night, or it's very far from night. Ah yes, that is how it works! Except the red thing doesn't move around, it's that thing". From then forward she oriented herself to this clock, and paid attention to light and behavior patterns tied to it. Interestingly, she was still baffled by the same animation that confused others for the rest of the game, commenting on it several times, "I'm going to try and figure out this thing that pops up, every time the night finishes". Several players actually commented on the spinning dial, with Isaac and Letty figuring out it was a sort of "clock", and Emery never figured out what it was.

Hiram observed a grid of light-colored tiles centering on a sleeping character and stated "this guy has got some weird animations going on here". After a moment he interpreted it as stemming from the character snoring, stating, "It said that he snores, so I assume the tiles lighting up are how far he can be heard". Note this is the same animation that Kari observed as described previously, that she interpreted as reinforcing the idea that her characters lacked oxygen. Fern's characters also faced the same snoring issue, however Fern came to believe the effect and lack of sleep was a result of characters being sick, having recently observed germs in the environment in the germ overlay for the first time, saying "oh they can't sleep because they are sick. Usually when I'm sick I can't sleep. Well, I can't sleep that well". The characters were not sick, but having seen germs in the environment moments prior, Fern came to believe they

were, and this contributed to the animation and her characters not sleeping. (They were in fact being awoken by the snorer).

Weighting Visual Phenomena

A major theme in interpretation of the game space is players giving great weight to visual phenomena, as in a great many circumstances visual information was used more than textual information and even iconography. While textual interpretation and its subordinate themes remain an important source of player interpretation, the weighting visual phenomena theme represents the strong tendency of players to interpret the game visually, even when other kinds of information are readily available. In some cases, this meant that players first came to understand, or only ever came to interpret, a piece of information through graphical cues as opposed to textual clues. In other cases, this meant that players gave great weight or outsized importance to a circumstance based on the visual presence of a component, relative to other layers of information, notably textual data, and especially quantitative data.

The most frequent area where a visual component led to weighting was the atmosphere. Greta exemplified a common type of statement when looking at the oxygen overlay, “Well the red stuff is unbreathable, and there's a lot of red stuff”. Hiram also referred to “red” atmosphere, “When I put the oxygen diffuser down, it showed the oxygen overlay, and there's like red down here, and typically red is bad.” When Isaac took a longer moment of time to look at the oxygen overlay, he said “I did not know there were large amounts of unbreathable oxygen... it says over here for the oxygen overlay that there's unbreathable oxygen over here.” He was actually pointing to an area of the map with carbon dioxide in it but continued to refer to it as “unbreathable oxygen”. Later in the game, he also began to refer to it as “unsafe oxygen”, “I'm going to try and get them safe oxygen. It looks like there's not much more unsafe oxygen... oh that's not good. It looks like there's not enough safe oxygen over there, so I am going to the

oxygen diffuser.” He even inexplicably started referring to oxygen diffusers as oxygen purifiers, “It looks like it's getting a little safer. I need to build another oxygen purifier thing over here.”

Fern noticed one of her characters was standing “in a red area” on the oxygen overlay, where this “red area” was a single tile of carbon dioxide. At that moment, her characters were standing in a chamber with a volume of 44 tiles, of which 41 were clean oxygen, and 3 were carbon dioxide. Gas tiles move around semi-randomly, and one of her characters happened to coincide with a single component of carbon dioxide for a moment, causing her to exclaim “Why is that guy standing in the middle of a red area? He should be avoiding the red areas!”. Darren did something identical in his second run of the game, “Oxygen wasn't very good over there for a moment... because this is an oxygen overlay. I assume the red is not very good.” The thing that “wasn't very good” was a single carbon dioxide component. This resulted in Darren changing his mining activities to the opposite side of the chamber, having seen the “red” square and wanting to get away from it.

The presence of carbon dioxide, even when it was in small amounts, or well isolated or contained, was enough to spark serious concern and strong reactions from many players. Bran saw carbon dioxide under his operating area, and declared “that's not good, why is everything bad? So everything's unbreathable now, it's carbon dioxide”. He then said, “it came from here, I'm pretty sure it came from here”, and referred to another chamber that also had some carbon dioxide in it. He even began to create interpretations to fill his gap in understanding, “It might have, because the tiles are loose”. (Regular tiles are impermeable to gas in this game).

Recalling Darren's example from above, he later saw some carbon dioxide beginning to collect below his main play area similar to Bran, and believed his failure was imminent, saying “I don't know, I'm pretty sure I'm going to fail now because there's not enough oxygen, but hey I'm just figuring out the game works, I have no idea how any of this works so I am absolutely fine failing everything”. This was ten minutes into play, and there was in fact plenty of oxygen, and relatively little carbon dioxide, however the visual rendering of several tiles of carbon dioxide

beneath his play area was enough to cause this belief. Darren was so discouraged by this scene, he quit the game and started a new one two minutes later. Later in this second session, the pattern continued as Darren had mined into a large chamber filled with almost entirely pure oxygen, and only a few units of carbon dioxide- at a ratio even better than the part of the map from where he came. However, the presence of six carbon dioxide tiles in the chamber complex was more intimidating to him than the three in the smaller starting chamber. He said, "I have no idea what I am doing, but these guys are not in good oxygen".

Another example of a phenomena where players tended to assign great importance to a visual rendering pertained to germs. Greta observed the characters deciding to disinfect things in the game on their own, and decided it meant they were disinfecting, "I've seen them spray some green stuff... that they're getting rid of the germs. That's just them, they just do it". She believed they did it because the number of germs had become a problem. (There were not many germs yet). Bran was extreme in his attempt to eradicate all germs, he felt that no germs should be in the environment, and disinfected every few minutes, often saying things like "I haven't disinfected things in a while, disinfecting time!". He projected this onto his characters, thinking they smiled after they finished building a sink, "aha yes. I built that so they could like, you know wash their hands before they eat something. Wash things. Yeah see, look at that! Yay they are happy now, they get to wash their hands". (The characters did not have any sort of special reaction to building the sink).

Bran also originally interpreted the germs as algae, "there's algae all over the machine". After being unable to disinfect it he stated "but there's not anything I can do about it. There's algae everywhere! I mean here look, all that yellow stuff is the germs." Later, after Bran interacted with the germ overlay numerous times, he seemed to internalize that algae is not a germ, and later verbally confirmed this. However, he did become very fixated on any amount of germs rendered in the environment, and obsessively cleaned from then forward. A short time later Bran said, "Wow, it's time for some disinfecting! I've got to disinfect the entire map! Even

an hour later after much of this, he said “nobody is taking this disinfecting thing seriously.” Not all players were too worried about germs, Celeste saw them the first time and said, “no one is getting sick yet”, and believed that her current wash basins were enough to stave off disease for the time being. However, most players reacted to a small number of germs as at least a moderate threat.

The temperature overlay is another example where players assigned great value to visual representation, irrespective of other data. For example, unless they are dead, the temperature overlay will render characters in shades of yellow to orange depending on how warm they are, while cooler objects in the environment are greener and bluer, and hotter objects are deeper orange to red and dark red. Axel opened the temperature overlay and exclaimed, “That's not good. They are red and yellow... I think they're cold. Oh, wait no they're hot! I have no clue... I don't know why they are hot, they are red, they are scorching”. He believed they were overheating because of how they were rendered in the overlay and did not seek to check their actual temperature with a tooltip. Fern saw the overlay under the same circumstances, as her characters were cold, and said “I guess green is neutral? I don't understand why they are cold”. Darren interpreted temperature in a somewhat opposite way, thinking the environment was cold because it was greener relative to the characters, “It's cold as well... it says. But I don't know what makes temperature go up”, and sought a means of increasing the temperature in the environment, even though the local environment was temperate.

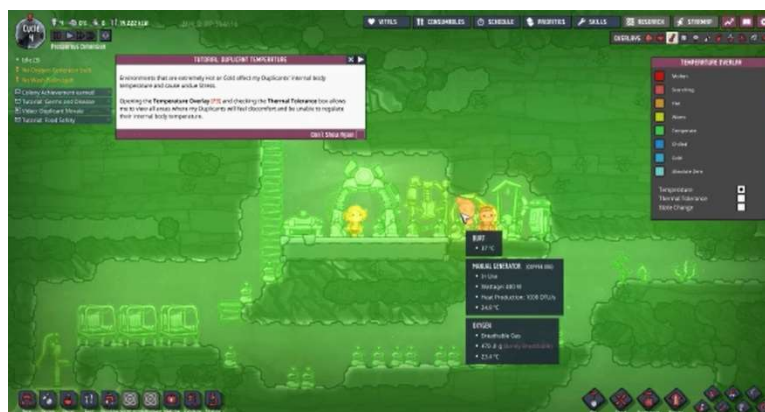


Figure 5. Axel examining the temperature overlay, believing his characters were overheated.

At one point Axel observed an animation of yellow bubbles coming from bottles of polluted water and assigned special relevance to it. He stated, "Why? I'm seeing yellow balls... that doesn't look good. Do I just sweep it up? I think it's this polluted water." He subsequently could not figure out how to "sweep" up the fluid bottles and left them on the ground. However due to his perceived risk of that set of bottles, he put some effort into trying to figure out how to get rid of them first. Though Axel considered it a serious problem based on the animation, the amount of polluted oxygen there was actually quite low.

As a final example, one player even assigned unusual importance to data visualization on the character "vitals" data table. Fern interpreted the order of character data in the as an ordinal stress level and concluded one character (Caroline) was the most stressed. In this data table, stress values are actually represented as an abstract percentage from 0% to 100%, but she did not read that data and relied on the order they appeared stating "who is more stressful maybe... the person who is most stressful is the person on top. The person who has more stress... who is stressing the most, like this one is really worried, "oh no we are going to die here!" Fern then began to try and find reasons why this might be and decided the reason might be because she hadn't eaten yet that day. In this way, she was developing interpretations for things that were not currently issues in the game.

Real World Models

The third superordinate theme that emerged from the data is "real world models" referring specifically to how players used their own mental model (or schema) for how the world works, categories and classification, and their own understanding of real-world behavior to interpret things that were happening in the game. This superordinate theme is not composed of

subordinate themes, but there were four areas of focus that players explicitly used real world models to interpret most frequently- power, liquid, atmosphere, and character behavior, though there are examples involving most of the systems in the game.

Power Models

Power models received a lot of attention from players, due to their importance in powering life support systems and other equipment. Getting a basic circuit working was a focus for most players, and how they made sense of the power tools varied. Fern spent a lot of time in the power overlay and attempted to locate objects in the game space colored the same as colors in the legend. "So building power, I think this means like... well I don't know about this because there aren't any of these colors, everything is gray and white. But there are some things, inactive? I don't know how to activate it. I don't know what could be their power source". Fern eventually noticed she could build a battery. She then stated, "I think, that's what will like make the power and everything. I think I need a battery because batteries power things", but it didn't work. Bran also initially built a battery attached to an oxygen generator with a wire, which also didn't power it. At first he believed "no power, that's perfect. Do we need like a secondary battery?" Isaac also built a battery immediately adjacent to his first oxygen diffuser and connected it with a wire. However, in this case, he realized very quickly he also needed a generator, "It has no power... I think I'm going to need to build a generator. Manual generator. So, I'm going to put that right there".

Fern was among the players to initially expend resources to build a battery alone, thinking it would power her circuits. During Fern's second playthrough, she built a large circuit before powering it up, and while she powered the grid with a generator, she still put a battery in series this time, thinking it was still a necessary component for the circuit to work, not just store power. (Circuits work with or without batteries). She also ended up building a second manual generator, not for the extra capacity, but "I think it will be really practical, if I do one manual

generator on one side and one on the other” and expressed a strong interest in reducing the number of wires running through her base. Later, she was unaware her circuit was overloaded, and melted a wire. This prompted her to begin looking for ways to regulate power, and she discovered transformers and built one, and very quickly internalized what function they serve.



Figure 6. Fern overloading her sole circuit

Greta came at the problem from the opposite direction. Having built a power generator first, she realized a battery could store power when it wasn't in operation, “stores power from generators, loses charge over time. So, I guess they don't have to be on the generator all the time if they've got a battery, since it will still be going.” Hiram also understood from the outset that batteries only store power and made this part of his broader power system. Later, as more power buildings became available to him, he very carefully read their names and operation details, and inferred how they are used, gaining an understanding of wire bridges and switches.

Laying wire created several challenges. Hiram built his first circuit very quickly and efficiently and powered his food production building. However, when he ran wire through the floor to another area to set up an oxygen diffuser, he didn't realize he set one wire command one tile too far for his characters to reach, so they built the entire circuit except for that one tile of wire. Hiram noted the no-power icon and interpreted the lack of power as insufficient generation as opposed to an open circuit, prompting him to create another generator, “I should

build a second one of these. To get more power to the diffuser.” Hiram proceeded to build the second generator and add wiring, but just over two minutes later, when he was reviewing the power overlay, he realized what had happened, saying dryly “that’s probably an important thing to connect”. Note however, Hiram felt that the manual generator was unrealistic, “the manual generator feels a little bit overpowered when compared to reality. I don’t think people can create that much energy from movement.”

Kari thought through all of the early game power buildings available, “Maybe I need all three things... well okay, because with the manual generator they are going to have to be generating power. But I don’t think that I can just plug that into the oxygen thing, so I might also need a battery to store up extra power. But I think I’m just going to build the first thing and see how it goes”. She proceeded to experiment by building a generator, an oxygen diffuser, and then some wires and a battery, based on her existing model of how she thought the basic components behaved.

Liquid Models

Managing liquids was a vexing problem for many players. Most of the participants built storage containers for solid materials, and figured out how those worked, but the game system handles liquids differently. When there is free liquid in the game, and characters mop it up, a system action generates a new component that represents a container of the liquid. The sweep command in the game will mark loose components on the ground for storage, and characters will store them in appropriate containers based on the item type, and storage options such as bins, ration boxes, and refrigerators. Managing fluids is more complex, and requires bottle emptiers or pumps, and specialized liquid storage tanks. Players would notice the “sweep” icon on fluid containers and took this to mean these containers could be stored. Some players like Fern noticed the icon was red, and that it was “blocked” from being stored. Greta was faced with a conundrum even before this point, “I’m trying to figure out how to bottle stuff”. She observed a

coherent node of polluted water that had fallen into her fresh supply and tried to conceive of ways to remove it. Hiram thought characters might not be able to manage these containers, “there’s also water all over the floor, in bottles, it doesn’t seem like they are picking it up, I wonder if it’s because they can’t.” Jade became very flustered at this same quandary and attempted to solve it by building several more storage bins in different locations to see if that would enable her characters to begin storing liquid containers.

In a consequential event in his game, Bran was mining and breached a barrier between his base and a chamber of water, which resulted in a massive flood throughout his base. The game actions available for small amounts of water (mopping) are not available for large amounts of water, which as large fluid components must be managed in other ways. He became very excited, paused the game, and sought ways to do damage control. He noted that the mop tool was for cleaning up spills and attempted to use it on huge pools of water, to “deflood the place”. This didn’t work, which resulted in a roadblock for him “I don’t understand what’s going on now. Everything is just going insane”. He tried again several minutes later, “Everybody ready to mop some things? Let’s do this. Let’s do it!”, but when it didn’t work this time, he interpreted this as his characters having given up, “too much liquid to clean, no wonder you guys gave up.”

Some players interpreted the behavior of water in the game in light of how they thought it behaved in the real world. Early in her session, Greta noticed that the water in a complex series of chambers changed, “Well the water evened out, so I’m assuming it went over here. So, the water was kind of going up at a slope, but now it’s just a straight line. It goes lower down so I’m assuming that the water filled that space”. She was confused as to why the water started at a slope in these chambers at the beginning of the game but made sense of the change by invoking what she knew of fluid behaviors. Later in the game, Greta observed the tooltip on the pitcher pump and noticed the water available to it decreasing “this number is going down... this number, water... liquid available so I think I have to clear this so they can reach more”. It had

dropped so only about 80kg of water remained available. This realization prompted her to clear some material beneath her pump pipes, which solved the problem, “oh yeah see now it's up again, now it's going up.” After this action, another 3,000kg of water became available. Despite the large amount of quantitative data available to players through tooltips, this was one of the few incidents where a player paid attention to quantitative attributes of game components, let alone used them to preempt or solve a problem.

Hiram was temporarily confused when he had his characters mop up some polluted water and ended up with some clean water at the edge of his clean reservoir, “it says its water, I'm not sure where that came from. Oh, it's because some of the water got in here. They probably mopped up some water.” Interestingly, the polluted water was so deep that it just barely spilled over the clean reservoir, but due to the way that liquid units are discretized into components, the unit at the edge of the spill created a container of clean water at the boundary. This is one of a few examples where a consequence of the programming created a quirk that confused players.

Storing fluids was a challenge for all players to figure out. Greta saw some text which led her to believe she might need to empty fluids into the ground, “I think it said something about empty. Do I have to empty it somewhere? Like do I need to dig out something? But there isn't really a lot of space.” She proceeded to try and devise a strategy to dig a pit in which to dump polluted water. Hiram took the same approach and dug a pit at the edge of his base as a place to fill with polluted water. He built a bottle emptier at it's edge and was pleased that “we're getting rid of all the bottles around the place.”

Plumbing was a final area of liquid management where some players did experimenting, and attempted to build systems. Hiram felt that building a plumbing system should be “common sense”, and began establishing showers and flushing toilets as soon as he could. He checked the plumbing overlay, and worked his way through it, based on his understanding of plumbing systems, “So I would assume that this is the output, this would be input, I don't think... and

since the output of a lavatory would be waste, you probably don't want to connect two outputs together". He eventually set his system up to dump wastewater in a chamber already filled with carbon dioxide, believing that the waste water would also emit polluted air. Similarly, Bran believed that gasses emitted from the toilet contributed to the suffocation of his colony, "that's the reason why they died... the turds are emitting polluted oxygen. This is the stupidest way to go. Suffocating from a turd. That's a really weird way to go". (Smells and polluted oxygen did not contribute to his colony collapse).

Atmosphere & Gas Models

Many players used various models they had about how gases behave to interpret the game, and design solutions. Darren was digging out his base area while preparing to set up oxygen generation, and said he believed that digging a chamber wider would impact oxygen negatively, saying "that actually might decrease it by making the area bigger, I'm not sure". This assumption was based on his understanding of gasses expanding to fill a chamber, and in no part based on information available in the game. However, he was correct as this is indeed the way the game functions.

While several players such as Fern and Letty expressed that they didn't know what chlorine gas was, Hiram based his approach to the gas on what he knew "Oh wow, there's chlorine down there, and hydrogen in here. Chlorine means you can't go in there, you might die. Chlorine is pretty poisonous from what I know of reality. I think chlorine gas has been used in war." Hiram understood algae can scrub carbon dioxide and make oxygen. However, he thought entire chambers of pure oxygen were unrealistic, noted the lack of nitrogen in the air, and this didn't fit with his model of the atmosphere: "I'm not sure you can create breathable air out of just algae, especially since atmospheric air is mainly nitrogen, so like, actually oxygen is incredibly poisonous. There's this dude once, he tried to... he tried to make a diving suit and in the tank

that he would use to breathe out of, he put 100% oxygen in there and he died, because it was so poisonous.”

Numerous characters encountered issues with atmospheric pressure, as did Jade. At one point during play, Jade’s characters’ eardrums began popping, and she initially had no idea why. She hovered her mouse over the “popped eardrum!” text associated with a character and said “How do I fix that though? It says they all have popped eardrums, I don’t know how to fix that.” She thought for a short time it might be because of sounds, “I guess the sound of breaking? I guess.”, Eventually she realized the tooltip provided more context, reading, “It says exposed to over pressurized area that popped their eardrums”, at which point she decided that very high air pressure could cause eardrums to pop.

Previous incidents referenced the dominance of visual information in the game, and several referenced carbon dioxides and layers such as Isaac saying it was bad to inhale. This general idea of CO₂ as “bad” fed into a common model of the atmosphere as “breathable” gas being safe, and all “unbreathable” gas being poisonous. For example, Jade also made note of carbon dioxide in the atmosphere, saying, “oh... carbon dioxide, isn’t that poisonous? Isn’t carbon dioxide bad? Am I just wrong? Unbreathable, okay...” In the context of the game, the “breathable” scale simply measures the availability of oxygen, with breathability decreasing either due to low or no pressure (vacuum). Some gasses are harmful (like chlorine), but oxygen and carbon dioxide can be inhaled without problem.

Other Models

While power, liquid, and atmosphere models from the real world frequently informed player interpretations, players used their real world understanding to make meaning of a wide range of game phenomena and behaviors. Many of these pertained to characters. A frequent example of players interpreting phenomena related to characters pertained to the “sore back” condition. When characters sleep on the floor as opposed to a bed, they will have a “sore back”

for a while, which decreases their productivity. Several players such as Bran interpreted the sore back as caused by too much work. For instance, Fern said it was because “I made them do a lot of work, and “Oh, at first I thought a massage table might not do much, but maybe it would”. As a result, Fern expended resources building a massage table to attempt to alleviate sore backs. (The sole function of the massage table is in fact to reduce character stress, which was quite low for Fern’s characters). Celeste also believed the “sore back” condition was because of “all the digging”. Bran came to the same conclusion, and also built a massage table for the same reason. Indeed, on the morning of his 10th cycle as his character rose from the floor, he read “sore back!” out loud as the character received that condition, and still stated “use the massage table”. And Greta originally believed sore backs came from work, until witnessing a character animation, and then stated “Oh wait yes, cots. They have this sore back when they get up after they sleep, they kind of stretch, so I’m assuming that means their back is sore”. Other players, such as Axel and Jade, immediately interpreted that sore backs came from characters not sleeping in a bed, as Axel noted “oh do you need beds? Is that why you have a sore back?”

There were many short examples of problems in the game that were explained by players making sense of what the characters might be feeling or thinking. When Axel did not have enough resources for his characters to build a ladder, he was confused as to why they weren’t following his build orders. He incidentally gathered materials in the process of mining that enabled his command to be executed, and Axel believed it was because his characters had since slept and cancelled some other builds (as opposed to him previously not having enough materials). And some players had mental models for what abstract social dimensions in the game represented, and the effect they had in the game world. For example, Axel linked morale to productivity, stating “I want them to have better morale, so they get more work done, I don’t know if that is how that works”. In Axel’s model, morale was associated with productivity. (In the game, morale is related to skill development). Several players such as Celeste believed that the

abstract conversations between characters had particular meaning, and assumed it contributed to morale generation. While the conversations don't actually have any real meaning, socializing does in fact increase morale.

There were many instances where the "expected behavior" of the game environment was simply what the player would expect to happen in the real world, as most of the systems in this game are designed to include. When this differed, sometimes players struggled to interpret what was happening. For example, Fern was having trouble figuring out why her characters kept getting the "soggy feet" condition, and eventually decided it was because of the materials on the floor, "the dirt and kelp and stuff is all wet and stuff, and they have to walk on it, but not when they walk on the tile. I am going to have them dig a level lower so I can put the tile". In fact, the characters were getting soggy feet walking on soaked tiles as well, but Fern explained that because algae and dirt are often wet, that's probably why the characters' feet were wet. This in turn caused her to conclude the role of tiles in the game is to keep feet dry and invested significant material resources to tile her base based on this meaning. There are many examples of this type of expected behavior, such as Bran expecting soiled food to decay, Celeste believing seeds should be able to be planted directly in dirt, and Kari making sense of disappearing tiles by concluding they had eroded due to repeated liquid spills. All players assumed that germs made their characters ill, however, Kari linked calorie consumption as described in the character health data table with disease, "I think they need to eat a certain amount of calories in a day to be healthy, and then they won't like get diseases and stuff", demonstrating a model of health that includes nutrition determinants.

Kari realized that volume displacement was modeled in the game, when she began to create structures at the surface level of water, "maybe I'll put blocks... I'll have them dig these three, and then I'll put blocks along here so they don't end up falling in the water every time they want to go". As she put blocks in the water, it overflowed into another nearby area causing a small flood.

Nearing the one hour mark of her play session, as Fern turned her attention toward generating more food, she used her understanding of photosynthesis to expand her lighting plan, noting “I think I'm also going to put a lamp instead of a ceiling light here. I think they give off a bit more light, in some areas I don't need more light”. When asked what areas she thought she needed light, she stated “I think I need more light for the plants”, and proceeded to build lighting where she was establishing plants. Fern also believed that the asteroid didn't accurately reflect what a place without lights would look like, and said “I think they've been in the dark this whole time”. When questioned about this in her follow up interview, she said that the screen was “lit for the player” to see what they were doing, but after seeing the option to build lights concluded her characters had simply been operating in the dark until she built them lights. (In fact, no player observed the fact that characters worked slow without lights, and faster in illuminated areas). Celeste also focused on food production earlier than most players and explored for a way to plant seeds directly in the dirt. This one is on top of metal ore, but I don't know, I wonder if I can just plant it in whatever. “Axel observed some bugs crawling around on a plant, and stated “Oh? Is that a bunch of bugs crawling all over it? Why does it say its harvest ready? It doesn't look ready, it looks like it has been infected... but it's not. That's weird.”

In one case, Fern built an outhouse, the building for which is listed under the “plumbing” tab. There was no dirt in it, so it was out of order”, and Fern said, “ah, I need to connect water! Because I need water in a toilet” and proceeded to spend some time trying to figure out how to attach pipes to the outhouse. Eventually she realized that water was not in fact necessary for the outhouse, as it only used dirt. However, during this process she opened the plumbing overlay and observed the legend to the overlay and began to outline what she believed to be a working model of a plumbing system, exploring the concept of pumps, piping, and output pipes and mapping what that would look like in the game.

Players also made decisions in the game based on their understanding of how ventilation systems worked. For instance, when Bran observed the cold symbol above one of

his characters for the first time, and immediately looked toward the ventilation building menu, while saying “ventilation, ventilation”, and thought that he could design a heater system. He ended up abandoning this project, but ventilation as modeled in the game can in fact be used to move warm and cold air around to impact environmental temperatures. Kari had the same experience as Bran, temporarily trying to find a way to build a heater with the ventilation system, but then gave up. Isaac also spent a significant amount of time trying to figure out how to get a ventilation system working, not to impact temperature, but to move oxygen throughout his base. He strongly tied the concept of ventilation in the game to moving breathable air around.

A previous incident described how Kari’s real-world beliefs about lighting inside an asteroid actually reinforced an interpretation that the darkness associated with the night cycle was related to her characters suffering from oxygen deprivation (when they were sleeping). Kari also questioned this and attributed the visibility in the game to the shine bug creature that players periodically encountered. “I’m assuming that this is the thing making the light, because if they are in caves, isn’t it going to be a lot darker?” And just as Kari believed that characters were passing out due to lack of oxygen, she also attributed them being cold due to a lack of oxygen, as she believed oxygen stores heat. “It seems like they are cold. Well, when there’s no oxygen it gets really really cold, so it’s probably that. When asked to elaborate on that she said, “I think it’s because the oxygen traps the heat, but I don’t really remember.”

Player beliefs about materials was another common area where players drew on real world knowledge, and these interpretations varied in impact. Hiram said “hey there’s coal up there, that’s probably good. It probably lets you heat stuff and power stuff.” On observing pockets of fertilizer in the world, Hiram said “fertilizer? There’s pockets of poop?”, and clarified he took it to mean that he believed they were pockets of buried excrement, as that was his understanding of what fertilizer was. Bran had a different view, “Fertilizer? Fertilizer is a human made thing. Why would it be here?” Jade was confused as to why various things she had created were made of sandstone, “Why is everything made of sandstone, that doesn’t make

sense.” She was unaware that materials she had mined were used to make these buildings by default, and other materials could have been used.

Participants often reached for a “real world” explanation even for elements of the game that are more fantastical. For instance, in Kari’s session, a block of oxylite had fully used itself up, and left a hole in the ground. Kari noted this, “oh, why is there a hole there” and decided it could be player caused erosion, “I dunno, maybe the dirt wears away as you walk on it.” Only when it happened again later, Kari eventually realized what was going on, “I think this went away because they are using up their oxygen, so I’ll look into that. Those like oxygen blocks.” Axel too understood that oxygen needed to be coming from somewhere, and when he finally looked at the oxalate tooltip he realized it was emitting oxygen, stating “what is that... oxylate... ohhh it is giving oxygen here, that’s why we’re not dead yet, okay.” And eventually as Kari looked for other sources of oxygen, she showed she understood the algae terrarium as related to how plants photosynthesize, “I think it’s probably using the thing of like how plants create oxygen.” Greta also expressed understanding that algae was a plant and emits oxygen and wondered if the other plants in the game also emitted oxygen. While several players came to this conclusion, a prior example noted Bran believed plants respire with oxygen. These sorts of one or two player exceptions prevented many “common knowledge” concepts from being included in the list of “common understandings” at the beginning of this section.

In a few instances, player interpretations were mediated by their own direct experience with the phenomena. Earlier examples noted that some players, such as Axel and Fern, were initially drawn to copper due to its color. Hiram extended this further, connecting to a personal experience with specular reflection from an object, explaining, “I just realized, the shine on the copper moves when you move. But it’s cool. It kind of reminds me when I noticed in real life that shines move when you move”. When asked to elaborate, Hiram explained, “it was recently, I was looking at something shiny, and it moved, and I moved, and I was like “whoa”. It was a car. It was very recently”. And while many players interpreted cold characters as stemming from a

cold environment, Hiram was one of a few players who interpreted characters getting cold due to being wet, saying “they are all saying it’s cold. Probably because they were just standing in liquid.” He confirmed this later when his characters got wet again, “Yeah, standing in the water definitely makes them cold.”

Hiram credits understanding evaporative cooling, and his familiarity with Celsius for assigning this meaning to the phenomena, “I was looking at the temperature. 22 degrees Celsius doesn’t seem that bad. I have friends that live in countries that are not America, so after a while you just sort of learn it.”

Game Mediated Interpretation

A fourth superordinate that emerged from the data is “game mediated interpretation”, defined here as the act of players interpreting the behavior of the game *Oxygen not Included* through the lens of video games in general, or a different specific video game. This can be succinctly summarized as players expressing an expected behavior of some game component or system, based on experiences in another game they perceived as similar. Interpretations within this theme often led to strategies and actions in line with what players knew to be effective in other games. Of the four superordinate themes, this is the most fully situated in games as a media domain, and represents an explicit finding that players interpreted a game through and came to understand game systems through familiar game design patterns and gameplay loops. The subordinate themes within game mediated interpretation are “general gameplay patterns”, and “model from other games”.

There is a subtle but critical distinction between the subordinate themes “general gameplay patterns”, and “model from other game”. General gameplay patterns refer to a player’s interpretation or expected behavior of a game, stemming from familiar *general* game forms and gameplays loops as described in Chapter 2. “Model from other game” refers to a

player's interpretation or expected behavior of a game based on another *specific* game they have played or know about. *General* and *specific* here are used in the same way that $y=4x+2$ is a specific line, but $y=mx+b$ is the general form of a line. Sometimes players mention only a single specific game as a source of comparison or interpretation, and sometimes they reference the general form of behavior of "games". In the latter case where players describe a "type" of game, sometimes they reference a specific game as an example, but in context they are using it as an example of a class of games or game behavior.

In conjunction with players making predictions of expected behavior based on other aspects of the game they were in, and the superordinate theme "real world models", these two game themes provide the basis of an additional classification of interpretation sources. Table 7 below lists the four primary interpretation sources in the data, which led to player interpretations and expected behaviors in the game.

Interpretation Source	Example
The Real World	"So, the water was kind of going up at a slope, but now it's just a straight line. It goes lower down so I'm assuming that the water filled that space" (Kari)
This Game	"Since the wires could be built in empty space not connected to anything, I think I could start the plumbing pipes that same way so the oxygen can get better in that area first." (Celeste)
Another Game	"It seems like a kind of natural area, like a cave, from my experience from <i>Minecraft</i> , there are more ores in caves." (Fern)
General Game	"The main material you always want to start with is wood. Wood is like, usually the most basic thing you always start with in a video game." (Bran)

Table 7. Interpretation Sources

General Gameplay Patterns

Every player made some sort of comparison of *Oxygen not Included* to another game. The most common comparison was made with the popular game *Minecraft*, most players made this comparison, including two of the three “low to no” experience players. For example, Jade said “it seems like a 2D version of *Minecraft*”, and Emery said, “it reminds me a little of how *Minecraft* is”. Isaac said it reminded him of “sidescroller games, even though it is not a sidescroller”, and *Terraria*. Greta also said it looked like a “platformer” game due to its 2-dimensional side perspective. Many players such as Greta and Bran compared it to *Terraria*. Kari also compared it to *Terraria*, and said it had the “same kind of vibe”, and also compared the behavior of the characters to *The Sims*”, “this is kind of like *The Sims*. Just the way you have them do tasks, and then it like takes them a little bit to do them.” Hiram said, “it reminds me of *Terraria*, or *Starbound*”, and later compared it to *Stardrive*.

These initial ideas about what other games *Oxygen not Included* is similar to how some players approached and understood it. Hiram’s first thoughts about the game were, “it looks like I’m underground. It reminds me of *Terraria*, or *Starbound*”, were specifically due to its perspective and presence of ores and crafting. This led to an explicit expectation about several specific aspects of the gameplay loop such as “advancement”, “getting more tools”, “research”, etc. Furthermore, Hiram expanded on what he believed the role of research would be in the game, “It helps you get more stuff. Allow you to build more things and use more things that you find. That’s usually what research does in games”. Stemming from these beliefs, Hiram structured his understanding of what was to come and what he should do based on his experiences with this gameplay loop in prior games (and in fact, they are very similar). Based on his experiences in other games, Isaac believed “food is going to be scarce, and there’s going to be a lot of stuff trying to kill me”, and as noted previously, he used tooltips extensively for the first several minutes in the game to try and understand what each component was, its attributes, and inferred how it might work before digging deeper into executing actions. The belief that he would be fighting alien monsters based on experiences in other games also prompted him to be

one of the only players to build a medical station early on, as he believed the game would have to be “healing” wounded characters. In this case, the gameplay is largely different, as most things that can harm the player are environmental, and alien creatures pose little direct physical threat to the player.

Darren was explicit that his pattern of game interpretation was modeled from experiences in other games, stating early on in his session, “I’ll try and get a resource and figure out how overall this works. That’s what I always do in games, and it never happens quickly.” He directly said, “given the way this game works I can expect some things about it”, referring to typical game design patterns and gameplay loops he had experienced. After Darren reset his play session due to his frustration at his perceived failure, he said “I don’t know, hey. So, I suppose you’re basically managing resources and you do things fast. I have a few other games like that, but they are a lot, you might say, I’m not sure what the right word is... calmer.” As he was creating his new characters, he also noted he believed the game “wanted him” to make good characters to succeed, saying “I’m looking at the characters, I’m looking at these stats. I’m just trying to make the stats be good, I think that’s what the game wants me to do.” Darren made an even more explicit comment about the underlying system of the game, noting how the game abstractly models aesthetics in the “decor” attribute of shine bug and plant components, saying “I don’t know what algorithm it uses to determine decor, but it’s pretty accurate whatever it is.” This is reminiscent of Fern’s earlier example, where her belief about what she thought the game designers probably intended influenced her misaligned interpretation of gases. In his post play interview session, when Darren explained how he went about generally understanding the game world, he said “I looked at my tools and inferred from the theme of the game”. Darren referenced *Factory Town* as similar to this game, “but calmer”, and his familiarity with this game influenced his play.

Many players brought their understanding of “how games work” into *Oxygen not Included*, and this sometimes significantly impacted their in-game behavior and strategy, as well

as their interpretation of components and the environment. For example, Axel was looking at skills, and came to believe achievements unlocked new dupes because many games behave this way (which was not correct), but this also caused him to pay close attention to skills and used skill systems from other games to understand them in this game. In another case, when Fern was struggling with her water pump, she eventually decided “I think they just need to “have” water”. When asked for clarification on what “having” water meant, she explained that in games, a resource existing in the world is different from interacting with that resource and then a player having access to it. Once a player has interacted with a resource, then they “have” it. This was similar to Isaac’s earlier example

When Bran first entered the game world, he immediately said “it’s kind of a bit like Terraria. It’s showing characters, and there’s a ton of materials here. In Terraria you can find many materials everywhere.” He then compared it to *Minecraft*, and later compared it to several mobile games. He immediately wanted to mine, saying “I’m trying to find out how to like mine or something.” Much of the terminology Bran used was common gaming language, such as “the sandstone that it dropped”, with “dropped” referring to the spawning of one game component caused by the destruction of another game component. Stemming from his understanding of other gameplay patterns, very early on Bran began to search the map for a source of wood, saying “wood is like, usually the most basic thing you always start with in a video game”. About five minutes later, Bran discovered a plant called “mealwood”, and exclaimed “Mealwood! That’s wood! It might be. Otherwise, it might just be called. wood is a pretty important resource in a game.” He became very fixated on trying to extract wood from the plant. (Mealwood does not produce wood, however, some trees can be grown underground later in the game, and these produce wood).

Fern even made a strategic decision based on what she thought a game designer would do. In another atmospheric interpretation referenced earlier, Fern extended her thoughts on the oxygen overlay and initially interpreted the color coding based on what she thought a game

designer might do. “Oh... I imagine the red is where there is no oxygen. That seems to be kind of shifting. Maybe it's the opposite... no no no, I think the red is where there is oxygen. Because there is so little of it in these areas where there's like nothing. I don't think they would just put areas full of oxygen in the game. Because that would be kind of easy, and you wouldn't have to worry about oxygen.”

In contrast with those who had experience with video games and understood familiar gameplay loops, there were clear differences in play among the three players with “little to no experience” in games. For instance, it took Letty a long time to get started, and she utilized a lot of guesswork and seemingly random “point-and-click” exploration, saying “I'm just trying all the buttons”. Letty mined the slowest of every player, clicking on single components to mine one at a time, and would only ever issue one command at a time in the game space, with long pauses in between. At one point, Letty paused the game and after 23 seconds of nothing happening, she stated “I think they are sleeping”. After another 83 seconds, Letty was truly stuck, so I interceded and mentioned the game was in fact paused. Letty's colonists all ended up dying about 42 minutes into her play session, due to suffocation from insufficient oxygen generation. She was simply not able to advance fast enough for her colonists to survive. However, Letty re-loaded an auto-save from ten minutes prior and was able to use the knowledge she gained in the minutes before her colony failed to build a power and oxygen system and was able to move forward in the game more efficiently. When asked in the post interview what were the hardest things to do, she said “figuring everything out. Like how to do... everything.”

That said, one player with significant prior gameplay experience, and who played this game “rapidly”, Isaac, also ended up with a suffocated colony. And a total of four players restarted their games during gameplay, although as discussed previously Darren's restart was prompted by his belief he would soon fail (although he was in good shape). Interestingly, Hiram restarted to benefit from the experience he had gained from his first hour of play, electing to restart his colony and start the game over for his second play session. His familiarity with the

game enabled him to build his core life support systems very quickly, creating basic water, power, oxygen, and waste facilities in just under 9 minutes from the start of his new session, much faster than any other player.

Model from Other Game

Many players compared *Oxygen not Included* to other specific games, as the previous section described. Sometimes interpreting this game through the lens of these other games, or even employing strategies that were useful in another specific game. For example, as Hiram was detailing how he thought the game would operate early in the game, he referenced several specific games “I know, um, in *Stardrive* research is a pretty big part of that game, it helps you get new ship models, and weapons, and stuff like that, to build more things.” As Hiram explored the “research tree” in the game, he explicitly stated his understanding of how it worked came from *Stardrive*.

About half of the players relied partly on *Minecraft* to understand this game. For example, Fern stated, “I’m going to create a mine over here. It looks like an area that has a lot of different ore. Like a good area for a mine”. When asked why she used that terminology she stated, “because of *Minecraft*”. Fern left the area for around nine minutes and struggled to identify ore, but later returned to the cave area and stated, “it seems like a kind of natural area, like a cave, from my experience from *Minecraft*, there are more ores in caves.” Fern designed her space strategy based on her experience with *Minecraft*, “I want three blocks because... usually um, it’s the same in *Minecraft*, I know that they can fit into two blocks, but I think it’s just... I always feel better when it’s like 3 blocks, because I’m more comfortable. It’s like, just above the limit, kind of, I guess” Fern also made some consequential assumptions based on other games, thinking that when she built a ration box it would come with rations, when in fact it is only used for storing food.

Bran also interpreted the behavior of fluids in the game as exactly analogous to “sources” in *Minecraft*. In *Minecraft*, a “source” is a node where a fluid, often water, will always flow from unless the source is eliminated. As Bran noticed polluted water appearing in the map, he tried to clean it up and stated “We need to like, get them by their sources first. They have like a little source that spilled... like kind of like in *Minecraft* there's like water, and if you want to block it you need to like, grab it by its source, and take a block and put it where it's pouring out of.” Bran attempted to apply that strategy to solve the problem (but it did not work, as this game as water components behave differently). When one of Jade’s characters wet themselves and created a puddle of polluted water, she didn’t notice that action, and was confused about the fluid, “polluted water? How did polluted water get here? I don’t know, I didn’t see a water source”. She also believed that there were nodes that should act as a “source” for water in the game, even polluted water.

Fern also interpreted a digging problem taking place in her game partly through the lens of *Minecraft*, and in this case the assumptions delayed her progress in the game. Her characters had reached some very hard materials that they could not mine through, and so did not attempt it, making Fern think they were avoiding the area, “I don't understand why they are not digging in certain areas. Maybe it's because I assigned it in the wrong way”. In fact, to dig through these harder materials characters need to be trained on the “hard digging” skill, which Fern had not done. Later, Fern would note that she didn’t think it was related to skill (and subsequently, material hardness), because in *Minecraft* hard materials could still be mined, they just took “more work” to get through. Later she would revisit these areas and notice the “firm” attribute of some of these materials from the tooltip, “Oh maybe it is very firm? It says very firm. So maybe they just can't dig it because it's too firm.” On an opposite note, several players such as Celeste noted how sand fell, and compared it to the way sand behaves in *Minecraft*, “The sand fell down from up here. It's just like minecraft I guess, sand falls”.

Interestingly, there were several cases where players interpreted something not from the real-world idea from which it is modelled, but how it is modelled in other games. As Greta began to explore further from her starting point, she noticed areas of the map with different collections of materials. “Oh yeah, slime and stuff, so I assume that's just like a different habitat, or biome”, and when asked how she came to that conclusion stated, “because of *Minecraft*”. Several other players described “biomes” this way, and Bran went even further into what this meant for these areas. For instance, he believed the area full of slime was “like a poison biome” and expected the terrain to have toxic features and poisonous creatures.

Supplementary Themes

Quantitative Aversion

A supporting theme to interpretation in these data is referred to here as “quantitative aversion”, referring to the fact that despite a very large amount of quantitative information in the game, players rarely used it to make sense of what was going on, or utilize it in play. Most of the quantitative data available in the game comes in the form of textual information within tooltips and data tables. Despite the straightforward and ubiquitous use of tooltips and wide ranges of uses of this information, players rarely used it.

There are numerous examples of how players could have used this information but didn't. For instance, Kari had built one manual generator early in her power system design, and as she added more electrical components thought she might need more. Rather than calculating or estimating the power she would need based on data available in the game, she made guesses, “I'll turn up the urgency of that so it gets done first.... cuz that'll be pretty quick and I can see if that's enough, or if I need to build more, if I need to build an extra manual generator”. Celeste did the same thing with her power system, simply adding another generator when she thought she had “too many things” on it, and Fern and Isaac did as well, even as

Isaac was initially concerned with the properties of his buildings. Similarly, Isaac noticed his max gas pressure issue was solved through the visual cue of his oxygen diffuser working, but never checked any quantitative values, nor did the other participants who encountered that issue, such as Axel, Bran, and Greta.

The majority of components in the game contain one or more types of quantitative information that are presented to players via data tables or tooltips. Many buildings have capacities, volumes they can hold, pumping speeds, power loads, oxygen emitted, etc. In one sense, this theme emerges from the “negative space” created in the game by observing what information the designers provided about these systems that players did and did not use. For example, no player looked at oxygen consumed and tried to match it with equivalent production. No player observed or attempted to understand heat transfer, storage, or ventilation in terms of quantitative information.

There are a few notable exceptions to this pattern among other systems. A previous example noted that Axel understood power consumption on a circuit. As he began to build out his power system, he mentally reviewed the sources of load and capacity on the circuit, “this does 240 minus power and this generates 400 power. I think this can do a maximum of 400 power, and this one takes up 240, and that one takes up 120, it should be able to do that I think”. Another previous example described how Greta was able to determine her water system was working by observing how the “liquid available” to her pitcher pump (in kg) changed after she made some changes to the space beneath it. And Hiram looked at his character temperatures to see if they were typical. Several players did note the numbers at one time or another, but they were very rarely used in interpretation, and almost not at all for system planning or design.

Proximal Problem Interpretation

A theme that emerged during play is labeled here as “proximal problem interpretation”. When players encountered challenges in the game, a pattern emerged where players would often link a problem or challenge with a nearby game component or area that had some sort of label on it or visually stood out in some way. Proximal problem interpretation refers to the tendency of players to interpret issues and problems as being related to things adjacent and immediately near the component in the game providing the feedback. The presence of a nearby labelled component was often the basis of player interpretation that that component or another nearby labeled phenomenon was the cause of the issue. For example, at one point Fern interpreted the problem with her characters sleeping as related to them being sick, as she had seen germs nearby, even though the germ count was small, and the lack of sleep was related to the characters not having beds.

As another example, Celeste noticed a small trickle of polluted water in her play area and thought this meant the plant immediately next to it was causing the issue. However, it was actually coming from her algae terrarium further away. There was information in the data table for the terrarium that would have helped her realize this, but she did not use it. In a somewhat similar case, Greta observed a fish in a chamber of polluted water and decided the fish was polluting the water, “I guess there's polluted water by itself. I guess the pacu makes it polluted.” (Pacu fish can live in polluted water, but they don't pollute it). Similarly, in a previous example Greta assigned responsibility for a problem to a nearby jar of polluted water, “I already mopped that up, but it is still making it unbreathable. Because it is emitting polluted oxygen”. In fact, polluted oxygen is very breathable, it is just unhealthy. The proximity of the liquid, which was labelled with text indicating it was emitting polluted oxygen, was near the area saturated with carbon dioxide, leading Greta to link this nearest component to the cause. In a similar instance, Bran observed a bubbling green gas near an outhouse, and decided that it was related to the outhouse being out of order, stating “what is the bubble that keeps on appearing? Oh, out of order, out of order. Everybody is going to keep peeing themselves until they drown in their own

pee.” In this case, the bubble was emerging from a container of polluted water in front of the outhouse, but Bran connected the issue to the outhouse due to how it was positioned adjacent to it. Again, there was information in data tables that could have helped Bran understand this, but he relied solely on the visual situation of the area.

Axel interpreted something similar with a seed. As he hovered his mouse over a plant seed called a mealwood seed, his cursor also happened to be near where there was a shift in the breathability of the air. He ended up interpreting the situation as the seed altering the atmosphere, stating “this seed... is changing how breathable it is. Why are they able to breathe in? That doesn't make any sense.” The seed resting on the border of more breathable gas was given great weight.

In a previously discussed incident, Kari concluded her characters were cold, and was thinking of possible reasons for that. Kari had also recently opened the oxygen overlay and noticed an area near her characters had “low oxygen” and stated “it seems like they are cold. Well, when there's no oxygen it gets really, really cold, so it's probably that.” Kari immediately connected the problem of cold characters to the adjacent area of “low oxygen” as opposed to getting wet, which had occurred earlier and much further away. Hiram interpreted a gray area of non-breathable air in the oxygen overlay as stemming from polluted oxygen, but in this instance it actually referred to a thin layer of polluted water (which is unbreathable). He stated, “it seems like they are doing something to the air... uh, well there's a yellow gas around it. Also, when you go to the oxygen overlay, it's just gray there”. In another atmospheric interpretation, Greta observed a graphical effect of small amounts of sparking blue dots in the atmosphere near the water surface (which represent clean oxygen in the game), and interpreted them as coming from the water, “there's particles coming from the water I think, like right here there's also kind of a bluish... unless that's part of the water”. The fact these particles were near the water caused Greta to associate them with the water, however their contrast with the rest of the air was higher due to the way game components are discretized into squares. Several players made this

interpretation, however some players understood it represented oxygen. For example, Axel also made note of this sparkling animation, but he did interpret these “particles” as being oxygen from early in his session, in one case referring to his character, “I can't tell if he is holding his breath or if he is fine. I mean there's oxygen right there, it's totally breathable.”

In another previously mentioned incident, Letty believed that one of her characters was stuck in the manual generator, and that the character was suffocating specifically due to them using the generator. She noted the alert notification that read “suffocating”, and stated it was because of a “lack of oxygen probably, but it started to happen when the generator was running”, linking the two adjacent things. In fact, her overall oxygen production was far below what her colony was consuming, a number she never checked.

Celeste noticed that adjacent to an oxygen generator that there was a space where the component rapidly switched back and forth between “oxygen” and “carbon dioxide” in the tooltip. The phenomenon actually taking place was that she had built the generator in the far side of a chamber that was filled with carbon dioxide, in order to oxygenate it. During each “pulse” of the oxygen generator it let out a unit of oxygen, which was both warmer than the chilled carbon dioxide in the chamber, and naturally lighter than the existing gas. So, each time an oxygen component was emitted, it rose quickly, and the space near the generator backfilled with adjacent carbon dioxide. This quirk of the game led Celeste to interpret

When Fern was having trouble getting her power system going, she had completed a circuit, but the system was still not working. She noticed her wire running behind the printing pod component and thought that maybe that was the reason she still had no power. She re-wired the entire area to avoid the printing pod to try and fix the problem. It did not, as the circuit problem was due to a lack of generation capacity much farther away. Letty also perceived this printing pod component as having attributes it did not, “I don't know, the printing pod says it has breathable gas and oxygen.” This was due an adjacent tooltip showing these words. This pattern happened several times, such as when Kari observed a rock and a plant on top of one

another, “it says ingenious rock (sp), but it also says uproot. I wonder if it's like a plant and a rock?”

In a few cases, players interpreted events that were simultaneous and near simultaneous as related. For instance, Letty clicked on the plumbing menu, just as the game made a sound and one of her characters “made a mess”, “um, there was a button and I pressed “build outhouse” and now its saying made a mess.” Letty interpreted the click as related to the character having gone to the bathroom. In the post-interview, Letty said she didn’t understand why it happened and was confused but maintained that she thought the two instances were related.

R2: Mental Models Results

The second research question in this dissertation addresses to what extent player mental models can shift during play. This research question assumes that as players experience and interpret information in the game space to address challenges and progress, and that this interpretation of the information and phenomena in the game will shift and move in closer alignment with how these systems function in the “real world”, as they make decisions and experience the gameplay loop. The analysis of think aloud gameplay videos revealed many instances where player understanding of game components, their attributes, and the systems they composed did indeed change through play sessions. Additionally, data revealed that player concepts and mental models often did not change, even when it negatively impacted their progress. This section characterizes patterns of mental model shift as players' interpretations of the game space unfolded and changed (or didn't) and describes key examples from each pattern.

Critical Incident Approach

These data are categorized and described using the critical incident technique, as described by Flanagan (1954). Within these data, each critical incident represents a discrete and related series of interpretive statements and actions during gameplay, revealing how a player's knowledge or mental model about a specific STEM concept does or does not change throughout play. After analyzing and coding gameplay videos with an open, descriptive approach, a structure began to emerge with most "critical incidents" falling into one of seven categories. Five of these categories represent a pattern of player mental model alignment with the real world, and the final two represent special cases that will be discussed separately. Throughout this analysis and discussion, the terms "incident", "case", or "event" are sometimes used as synonyms for "critical incident" in the narrative.

Each critical incident is bound by two specific points in the data. The first point is a point in the data that unambiguously shows an "initial position" that represents a players' *original* belief- or lack thereof, with respect to their mental model of one of the games systems, such as a piece of knowledge of some concept or system designed into the game. The second point represents a players' *final* belief- or lack thereof, about the same piece of STEM knowledge. In some instances, the critical incident occurs very quickly, across seconds, with these two points close to one another. In other cases they are far apart, by many minutes or even hours.

These results and discussion use three terms to describe a players' knowledge "position" with respect to a specific STEM concept. Note, the terms "aligned" and "differs" are adopted to indicate whether a players' mental model or beliefs align with the generally accepted scientific and systemic understanding of domain experts (e.g. "the real world"), or whether they differ. This analysis avoids the terms "right" and "wrong", especially since it turns out that from the perspective of exploring the game model, players develop understandings that differ from reality for reasons that are clearly tied to the limitations of the ability to model systems in the

game itself. In addition to models aligning and differing, players often expressed uncertainty or a lack of knowledge, representing a third position, “unknown”. Table 8 below articulates these three positions with examples from the data.

Aligned	Player mental model or belief aligns with the real world, as understood by domain experts
Example	Celeste stated an understanding that algae emits oxygen
Differs	Player mental model or belief differs with the real world, as understood by domain experts
Example	Fern stated a belief that copper was not a metal
Unknown	A player expresses uncertainty or lack of knowledge about a specific concept
Example	Greta stated she was uncertain whether distance along a wire affects power output

Table 8. Player Mental Model Position

Each of these “positions” represents the start and end state of player understanding or belief, and characterize the five patterns of mental model shift, representing a total of 115 critical incidents recorded during coding and analysis. In addition to these five patterns of mental model shift, two additional types of “critical incidents” emerged from the data. In these results they are described as “Model Boundary” incidents, and “Game Boundary” incidents. “Game Boundary” incidents are critical incidents where players developed some sort of realization or change specific to the game mechanics that support the game, but outside of the real-world behavior domains modeled in the game, such as controls, menu operation, task assignment tools, etc. They are intrinsic to the game, and often pertain to input, interaction, and the user interface. Because these cases took up some amount of player time and attention, they were noted during

coding and analysis, but they are not discussed in depth as they pertain more to the operation of the game than the scope of interest of this dissertation.

“Model Boundary” incidents are cases where players stated a belief that the game model was inaccurate, incomplete, or unrealistic compared to the real world. No game can fully model every aspect of every physical and social phenomena, and these statements by players represent instances where player understanding of reality differs from expected behavior of the game. Reflecting on the visual metaphor in table 9, these are the effects of the simplification of domains between the first and second diagram, as the process of game design simplifies real world behavior into a game model. Model boundary incidents represent instances where players commented on these differences during play. Table 9 Below presents the number of critical incidents in five areas of interest, as well as the number of model boundary incidents

Differs	Differs	29
Differs	Aligns	31
Uncertain	Differs	9
Uncertain	Aligns	35
Uncertain	Uncertain	11
Model Boundary		21

Table 9. Critical Incidents

Some final notes on describing these patterns are in order. First, the pattern “Aligns - Aligns” is technically a pattern exhibited by the data, however the players, who are all typically functioning middle school students, possess a large amount of knowledge about the systems represented in the game, and this task would be extensive and unnecessary. The incidents of most interest are where player understanding is incomplete or different than the real world.

Because player understanding of the components, and the systems they represent were so varied, and that the game models so many phenomena, it is impossible to establish a single common baseline set of beliefs that were aligned, shared across all players, and did not change across play. There were few common themes, and few aspects from the overall game model that every player explicitly commented on. However, there were at least nine sets of statements shared between ten or more players, with no differing understanding across these players. These statements emerged during the pre-game interview, as well as during gameplay. Beyond these statements, the data explicitly showed at least nine common understandings:

1. Characters need to breathe oxygen to survive
2. Characters need food and water to survive
3. Characters need to relieve themselves
4. Germs can make characters sick
5. Germs can be removed by washing and disinfecting
6. Power is carried across wires
7. Plants need water and light
8. Pollution is harmful to characters
9. Becoming too cold or hot is harmful to players

While each player operated with a large amount of knowledge from the outset of the game, there were many instances where commonly understood facts or models were not shared by one or two players, such as Fern believing copper was not a metal or Bran believing plants respire oxygen and emit carbon dioxide.

The model shifts are interrelated with player interpretation themes described in research question one, and stem directly from them. This section builds on some of these previously mentioned examples and introduces some new ones to illustrate each pattern. Examples of each type of critical incident are used for illustration. The section concludes with examples of game boundary critical incidents.

A few things are important to note about these results. 1. This represents a subset of player thoughts and understanding (aligned or misaligned) 2. They only represent what players

chose to say aloud, 3. Are a subset of total knowledge possessed by the players about the domains in the game, 4. Exclusive of game boundary comments.

Differ-Differ

The data contain 29 critical incidents where the player mental model had some aspect that differed from the real world before gameplay and remained different afterward.

For example, Bran expressed a belief that flowers respired oxygen, “can flowerpots actually use oxygen? I know they need oxygen, but could they bring out oxygen? I know that they need oxygen, but can they give oxygen like trees?” When asked to clarify, Bran stated his belief that trees needed oxygen to survive. At no point during play did this model come into alignment with the real world.

Player mental models of power systems and how they function were varied, and subject to change during play. A common example within power systems is player understanding of batteries, and their role in a circuit. Six players built batteries thinking these alone were sufficient to power their circuits. Fern was among these players, and she built a large circuit before powering it up, and while she powered the grid with a generator, she still put a battery in series this second time, she still believed it was a necessary component for the circuit to work at all, not just store power. In this case the battery became a proxy for power delivery for the remainder of her play session. For example, she was working on establishing food processing, “I’m just trying to figure out if this needs to be powered by a battery”, and while the battery in series did power the circuit she ended the game convinced it was required along with a generator. Notably, power requirements are listed in an information field for any building that requires it, but rather than look for this information, she simply decided to build it first to see if it needed power, “I might as well build it just to find out”. Despite the fact a key piece of Fern’s model still differed from reality, her understanding of circuits was still able to shift as she came to understand a circuit could support multiple loads in series, “If those two connect... it’s still

connected to the battery, technically, so if they build that..." (the circuit worked). "oh that's nice, I didn't think of that".

As with power systems, players had a range of reactions to atmospheric systems, and models remained unshifted. For instance, Axel decided to build his beds in the very bottom chamber of his base. This fact, in combination with the fact his sole oxygen diffuser was higher up in his base, made it so the air below grew very foul, and his characters slowly began to suffocate. Foul air occurs in caverns, such as the ones in the game, as oxygen rises and carbon dioxide falls. The game models both gas diffusion and separation by weight, and Axel even commented on the separation saying, "I thought there was oxygen here [lower] but it's only up here [higher]", yet his model of gas diffusion and separation never shifted. He addressed the situation by creating another oxygen diffuser in the lower chamber, which was unnecessary and wasted resources, even though it did in fact work to keep a continuous supply of oxygen in the lower area. He ended his session simply thinking that oxygen created near a diffuser stayed near it (ironically, not diffusing). In the follow up interview when he knew what "diffuse" or "diffuser" meant, he said he did not.

Many players' understanding of atmospheric pressure remained unchanged. In a previous example, Axel missed the role of high atmospheric pressure in preventing his oxygen generator from working, and his understanding did not change. Likewise, Bran observed that his oxygen generator was working intermittently, and did eventually notice the tooltip that read "max gas pressure", "max gas pressure... well it's working uh... I need more, and uh, my team's going to die". Bran believed it was working, but didn't understand why it only worked intermittently, and never realized that the chamber being highly pressurized was what made the generator stop working. In the same situation, Greta abstractly attributed it to the presence of carbon dioxide nearby, "oh... what does max gas pressure mean. Uhhh. Um. I think it's because the carbon dioxide...". Other players understood some aspects of atmospheric behavior but had other misinterpretations. For instance, Hiram encountered this phenomenon and stated "oh no there's

max pressure in there. That doesn't sound very good. It probably can't put anything into the air if there's already a lot in there”, which is aligned with how air pumps work in the real world.

However, Hiram observed (as with Bran) that the diffuser worked intermittently, and Hiram wondered “I don't know how suddenly it works all of a sudden when it's supposed to be at max. It's very strange. Something must be happening.” He concluded that gas must be “leaking out” of the chamber for this to be happening. So, while his model of pressure and air pumping was aligned, it was also the basis for articulating a behavior that wasn't actually occurring.

In another case related to gasses and atmosphere, Celeste expressed a belief that the generation of carbon dioxide by a coal generator could be countered by an oxygen diffuser, “I would need like another oxygen diffuser, because that emits carbon dioxide, so I'd need something to balance it out”. As in the real world, adding oxygen to an environment in the game does not remove another gas. This action didn't decrease the carbon dioxide in the atmosphere, and the diffuser didn't consume atmospheric carbon dioxide. It did, however, result in the use of extra resources, and an overall increase in air pressure. However, Celeste did not appear to notice as the only consequence was an (unobserved) quantitative increase only observable in tooltips on components of gas in the chamber, but they remained below a threshold that could cause other effects, so Celeste did not notice and ended the game still under her original impression.

Also on the topic of carbon dioxide, Hiram believed that inhaling carbon dioxide is inherently harmful, “because you kind of know, these people are kind of like human, and you kinda know intuitively breathing carbon dioxide is bad for you.” When asked for clarification, Hiram stated that carbon dioxide in general is bad. In reality, it is perfectly safe to inhale carbon dioxide, especially at low levels, and is not harmful to humans. Hiram retained the belief that carbon dioxide was inherently harmful throughout play until the end.

Many players also missed the evaporative effect of cooling in the game, particularly with wet characters and the fact it chilled them, actively attributing it instead to simply a cold

environment. Several players such as Bran, Emery, Jade, and Letty sought ways to warm up the environment through ventilation or heat sources. That characters were often cold bothered many players all throughout game play, and in her post-play interview, Jade even stated this was the game experience that bothered her the most, “they were always cold and wet, and I have no idea how they even got wet. And I couldn't choose that, it was annoying”. Despite the fact she also observed her characters were wet. Jade still believed her characters’ environment was too cold (it was in fact temperate).

Several other players that expressed an idea that wasn't aligned simply never changed it during play. For instance, Bran believed that the “organic” label on some components using the tooltip meant that they were “consumable”. This also came on the heels of him believing a “consumable ore” was one that could be eaten, and this simply never changed, as well as after declaring he believed a “sedimentary rock” was a “fraction of a rock... a whole rock”, which also never changed.

Differ-Align

The data contain 31 critical incidents where the player mental model had some aspect that differed before gameplay, but actually changed during the course of play to align with that aspect in the real world.

A previous example described Fern believing that copper was not a metal, and that she overlooked this resource when looking for metal in the game for a long time, to the detriment of her progress. She looked for quite some time in the game world for something she thought could be metal, “algae, algae, dirt, copper ore, sandstone, sandstone, copper ore, dirt, algae... wow, there's not a lot of metal, I don't know how to find metal. Maybe it just pops up?”. Not having access to metal inhibited Fern's ability to build anything electronic, nor advance in the game, for about an hour. Even approaching an hour in, she said “I don't think copper is metal, I haven't seen any metal, and I can't expand unless there is breathable oxygen.” Note, other

players had uncertainty in this area, for example Darren said “Does copper ore count as metal ore, or is it something different? I would say copper is metal, but I am not sure if it's classified as metal in general, or if there's a specific ore it is talking about”. When asked about this comment, Darren raised the possibility that the game terminology might differ from the real world. And Kari wondered the same, “copper counts as metal, right? Probably”. She confirmed this after she moved forward with her assumption. In Fern’s case, her model finally changed when she unintentionally mined some copper while opening up a cavern, leading to the visual cue of certain buildings becoming colored. Following this she decided that copper was, in fact, a metal.

Late in the game, Fern began to pay more attention to tooltips and classification. Fern noticed, “I think there are different categories. Like there are raw mineral, metal, etc.”. Other players observed the same thing, at various points in their play session, in several cases resulting in a shift. While the materials overlay was little used during any of the play sessions, Emery noticed that there were in fact a set of sorting filters in the corner of the overlay that allowed players to focus on particular material types. Emery had been stymied by not being able to find or “build a filtration medium” for the water filter she had created, thinking it was a physical object she needed to figure out how to create and insert. However, on seeing sand classified as “filtration medium,”, she exclaimed “oh, sand is a filtration medium”, and proceeded toward mining some.

Many players’ models of gas and atmosphere behavior changes over time as well. When Isaac encountered the max gas pressure phenomenon, he looked “to see if the oxygen is working... and it doesn't look like it's working. Apparently, this is still unbreathable. It looks like there's max gas pressure in here, which might not be good.” As noted previously, Isaac didn’t differentiate between different types of gasses and air, and still had a model where oxygen could be “good oxygen” and “bad oxygen”. This understanding led him to seek a means of “purifying” oxygen (air), “I might need to get some sort of oxygen purifier thing. Something that makes the oxygen not bad, I guess”. In fact, there was no “bad oxygen” not oxygen at all in this

case, but rather different unbreathable gasses. Early in her session, Celeste had the same belief, in describing where she chose to place her first oxygen generator she said ““because the oxygen is really bad down there, and because they are going to go in there a lot”, placing the generator in a location that was simply rich with carbon dioxide.

Isaac’s belief that ventilation was the solution to “bad oxygen” stemmed in part from his understanding that there was “good” and “bad” oxygen in the game, and that in his working model of a ventilation such a system might help “purify” it. In fact, once he established a working ventilation system, he went so far as to deconstruct one of his two oxygen diffusers that was in an area saturated with carbon dioxide. “I think I might actually deconstruct this. Because I don't actually need it anymore. I already have this other one over here.” A short while later, his ventilation system was pumping carbon dioxide into a small chamber of what little oxygen he had left, and all his characters began suffocating. At first he interpreted the situation as a lack of resources, thinking he stopped putting algae into his diffuser. This didn’t solve the problem. It was also at this point that Isaac realized oxygen tended to rise, “It seems like a lot of the oxygen is going up there, so he's not getting that much of it.” Two minutes later, all of his characters suffocated to death.



Figure 7. Isaac’s ventilation system, pumping the little remaining oxygen into this section of the base, as a character gasps for air beneath it.

In this case, Isaac restarted his game at a save point ten minutes prior and reflected on why his colonists died and adjusted his model of oxygen and ventilation. He worked very quickly from this point forward to ensure he maintained two functioning oxygen diffusers, and said, "I actually have an idea. I can draw out the bad air and put it somewhere else that I don't care about. Most likely somewhere way up here". While his concept of "bad air" didn't change, Isaac's solution worked as he pumped away air with much carbon dioxide (which works), which also incidentally lowered the pressure in the room and caused the oxygen diffuser to work more efficiently, which he noticed when he was inspecting how his system worked. After this, he expressed a revised understanding of how this system worked aligned with the real world, and even expressed an understanding that positive ventilation into a space increases pressure there.

The type of system in this category that most frequently saw a shift in player understanding was power systems, surrounding concepts of power generation and storage (batteries), transmission, load, and circuit behavior. All players observed that some systems require a power source early in the game, typically an oxygen generator, though sometimes a light or a microbe musher (food processor). The first thing several players did to start their power grid was build a battery thinking it would power the system. For instance, Letty said "No power... it needs a power source. So, a battery?" and proceeded to build one. It had no charge, then she decided the solution would be to build a wire from the battery to the generator. It still didn't work and began looking for a way to "turn it on" (the battery). And after about eleven minutes of feeling stuck, and cycling through various menus and buildings, she discovered the manual generator in the power building menu and was able to move forward. After this, she understood that generators create power, and batteries can store it. Fern built an entire circuit, and built the battery to power it last, on completion announcing "Yes, it's complete! But this isn't... this is no power. It says no power. Maybe the battery? The battery is fine... that can't be the problem". She struggled with the problem for several minutes, "Wow, this is a tough one.

The battery should be giving off power. Because that's how batteries work". Eventually she explored other buildings in the power menu, and wondered out loud "It has to be charged? But I don't know how to charge it. Yeah, I guess it has to be charged. But how would I charge it? Maybe a manual generator?" Fern experimented with building a generator, and when the system worked, her model shifted. As noted in the previous section, Fern's mental model of circuits and power generation changed, with one exception- she still believed a battery was a necessary component of the circuit (it is not), representing a case where some parts of a player's mental model became aligned through play, while others did not.

Players' initial positions about their models and beliefs came from a wide range of places. Bran initially built a battery attached to an oxygen generator with a wire, which didn't power it. When he noticed this, he stated "No power, that's perfect. Do we need like a secondary battery?" A short time later, like Fern, he finally considered the manual generator building, and said "manual generator... ooh, I did the wrong thing. I used a battery. I'm supposed to be using a manual generator." In his follow up interview, he noted he did really understand rechargeable batteries. "They (batteries) die" and "you throw them away". When asked if he knew about other kinds of batteries, he said no. Out of curiosity, I asked him how a laptop or a phone could stay charged when not plugged in, and he replied "oh... they have a battery. But the battery in the game looks more like the ones you buy at the store". Ultimately, he experimented with his circuit and took pleasure in explaining his final design, ". Bran: This weird little contraption I've made... so this powers to the battery, the battery powers to this, but also the battery power flows through this sometimes, and powers to this", all while pointing out the elements of the circuit in a manner aligned with the real world.

As a counterpoint to noting that several players never realized evaporative cooling was the cause of their character being cold (and that for the most part, local environments were temperate), two players that started with the same assumptions did shift their thinking. On reflection, and without a particular prompt, Kari realized that her characters were cold because

they got wet, suddenly stating “you know, maybe they were cold because they were standing in water.” She came to believe this just as her characters were bottling up water spilled on the floor, and she said seeing the containers of liquid made her realize that was probably what was making them wet. After this, she realized water could be used as a coolant in various ways in the game (which is correct).

Uncertain-Differ

Players expressing uncertainty about a concept and leaving the experience with a misaligned model due to the game was the least common model shift pattern, but did occur nine times.

An earlier example described how Jade did not know what a pneumatic system was and misinterpreted some text as defining pneumatic as “encloses areas without blocking gas flow” (interestingly, this is nearly the opposite of pneumatic). What she was looking at was a type of pneumatic door that simply allowed gasses to pass through and pressures to equalize on either side, but she came away with a misaligned idea of what a pneumatic system was.

One case involved Axel coming away with the belief that water in a closed system could be unlimited. Axel referred to his colony “running on its own” but grappled with the constraints of limited versus unlimited resources. “I think it would live by itself awhile. I mean it would probably run out of food at some point because we don't have infinite dirt or water... actually we have infinite water, just not dirt. I think that's infinite water, right?” Axel later referred to the fact polluted water from bathrooms could be filtered, and therefore the water was infinite. However, some water is lost through various other processes in the environment and is not in fact infinite. He did understand that the resource load on the colony would be greater, the larger it got and the more characters he added. “I think if you played for longer it would get funner, because you would understand more and your base would get bigger and it'd look really cool, thought there'd

also be a lot more managing because there would be more people, a lot more space to fill with oxygen, and a lot more food needed”.

Fern was not aware of the purpose of tile in the game, nor did she understand that evaporative cooling is modeled in the game and appeared unaware of how it functioned. In this game, tile performs several functions. It makes the ground even, characters walk faster on tile, it is easier for characters to clean, and players can put plumbing and wires beneath it. Early in the game Fern expressed uncertainty as to what tile was for and did not use it at all. Later, she came to believe tile was for keeping characters' feet dry (and this was connected to her previously discussed belief that open earth was making her characters' feet wet, although it was not). This in turn contributed to Fern's misaligned model of evaporative cooling.

Another critical incident described previously, where Celeste interpreted the oxygen generator as converting carbon dioxide to oxygen, represented a case where a player had an unknown or indeterminate understanding of this in-game phenomenon, but came away believing something misaligned with reality, that machines exist that can directly convert carbon dioxide to oxygen. Her interpretation intersected the interpretive themes of tooltip and proximal problem interpretation, and the limitations of the game's ability to fully model gas dispersion contributed to this belief.

Uncertain-Align

There were many situations during which players expressed uncertainty about something, but through the process of play came away with aligned models. This occurred 35 times.

Some of these critical incidents were related to power generation. At one point, frustrated from not having found metal ore, Fern stated, “I'm going to test out if one of the power sources are one of the plants” and proceed to experiment to see if plants could generate an electrical current. In her follow up interview, she stated she didn't know if plants could generate

electricity, “maybe they can, like an eel or something”, and added “also that could just be how this game works”. In her second session, Fern expressed uncertainty as to what a power transformer does and ignored it for some time. After she realized she had too much power on her one circuit after her wires melted, she began to experiment with a transformer and reduce loads on parts of her circuit using it. Finally, a prior example referred to Fern not understanding whether she could add loads to a circuit in series, and experimented with this and realized she could. (Though as mentioned previously, she still came away with the belief that a battery was necessary on every circuit). Other players experienced some of these issues, for instance, Isaac initially did not understand what a power transformer was or its role in a power system, but eventually also gained this knowledge. And Hiram eventually learned how a wire bridge worked in this same way.

As Greta thought through her own power strategy, she expressed uncertainty if distance impacted how far power could be supplied along a wire, “well I need to make one of these, so I need to power this and I'll also need to power other things. I don't know if distance from the thing changes how much power it has. So, I am just going to build it right here.” She proceeded to build her generator in close proximity, but as she expanded her circuit later, she expressed a realization that the length of a wire didn't impact the power it could supply.

Atmospheric systems also often fit this pattern. A few players realized that gasses in a cool, closed chamber can differentiate (causing foul air as one consequence, as explained previously). Fern eventually processed this saying, “oh this sucks, I really don't like they have to sleep in an area like this. I made it on the worst spot. Maybe cuz it's like... that's kind of hard, maybe cuz it's like lower towards the ground. But I don't know how that would work, it's just that I see that the oxygen is pretty good like up, so maybe it's that. So maybe that design thing wasn't that good an idea.” When asked to elaborate, she said she noticed the oxygen tended to rise, and the carbon dioxide tended to fall, and the consequence of her characters nearly suffocating at night was what made her realize that. Greta made this same realization late in her

session, “I think that the oxygen... does the oxygen go up? All this is still red...” and monitored the oxygen overlay until she concluded that carbon dioxide sinks, and oxygen rises under certain conditions. As mentioned previously, Isaac also came to realize this when reflecting on why his colony suffocated.

Several players were unaware that gas pressure was modeled in the game, or what its effects would be, and prior examples explained how several players encountered this phenomenon. In Jade’s case, her characters’ eardrums began to pop as she overpressurized her environment through excessive gas generation. She did not initially understand why, but the problem prompted her to begin looking for solutions. She eventually realized what the issue was after observing the “max gas pressure” cue from her oxygen generator (one of three sources of gas emission into the space). An earlier section notes that several players experienced this phenomenon, and never made the realization.

Other examples include Letty not knowing that algae could produce oxygen from carbon dioxide and water, but later coming to understand that it can, as well as how algae, combined with light and water, could “scrub” carbon dioxide from the atmosphere. Hiram also made this realization during his play session.

Model Boundary Incidents

For purposes of this work, model boundary incidents represent the twenty-one cases where player understanding differed from what was reflected in the game but were in fact more closely aligned with reality. These represent one of two additional types of critical incidents that occurred during data collection. These are cases where players stated a belief that the game model was inaccurate, incomplete, or unrealistic compared to the real world. Often these cases were the result of some surprise to a player, and sometimes resulted in dismay when they were not able to solve a problem due to the difference between expected outcome and what actually happened in the game.

For example, two players were surprised to discover the game did not model ground matter such as dirt as being capable of absorbing water. As Isaac began to struggle with bottles of polluted water piling up, he built a bottle emptier over a patch of dirt, thinking if he dumped it there “it probably goes back into the ground.” When his characters began to collect containers of polluted water, and send them through the emptier, the polluted water just ended up back on the surface of the ground and trickled back into his base. “Ohhh it seems like there's... I think I did something wrong with this. I think I did something wrong with them doing the water, I think I need pipes here. It just dumped everywhere instead of going into the ground”. He didn't do anything “wrong”, the game simply doesn't model water absorption by the ground. Kari had the same belief, and did the exact same thing.

Celeste also expressed dismay at the behavior of the same dirt component, but for different reasons, thinking she should be able to plant seeds directly in the dirt. "I got a mealwood seed, and I wonder if I could like plant it. This one is on top of metal ore, but I don't know, I wonder if I can just plant it in whatever. Like, dirt". Celeste sought a way to plant the seed in dirt but could not. As she soon discovered, even though plants can grow in the wild in dirt and other substrates, players can only plant seeds in specific buildings such as planter boxes, planter tiles, and hydroponic tiles.

Other players commented on the behavior (in formal terms, system actions or lack thereof executed by the component) as unrealistic. For example, Bran saw two connected stones “floating” in space, and said “wait a minute, wait a minute. Wait wait wait, stones are breaking the laws of physics!” If players mine around stones, they will appear to be “floating” (though the game is rendered in two dimensions it is implied there is a third supporting the stones). Bran also believed that a vegetable that had been marinating in human waste for three days should have made characters ill. “I betcha that thing is now... it's not! Huh! It was soaking in pee before, and now it's still really fine! The muckroot is fine. And it's been soaking in pee for two days. That shouldn't happen. It shouldn't be soaked in pee, and probably if they ate it they

should've died." Organic material and food decay is in fact modelled in the game with some level of complexity, and this food item was on its way to decaying, but Bran felt that after two days in pee it should have been inedible, and even harmful to ingest.

Hiram had several concerns about the "realism" of the model. First, Hiram observed that in the game characters could survive just fine in pure oxygen, which differed from his model of an ideal human atmosphere and what pure oxygen would do to humans, relaying a story of why he believed the atmosphere model in the game was flawed in this respect. "Atmospheric air is actually mainly nitrogen, actually oxygen is incredibly poisonous. There's this dude once, he tried to make a diving suit and in the tank that he would use to breathe out of, he would put 100% oxygen in there, and he died because it was so poisonous". This is in fact aligned with reality, as inhaling pure oxygen is indeed dangerous to humans. Hiram also noted, "the manual generator feels a little bit overpowered when compared to reality. I don't think people can create that much energy from movement".

Several players commented on the fact that the player and characters seem to be able to see inside the asteroid, even without a light source. This caused Greta to come up with an explanation to close that conceptual gap, thinking the glowing "shine bugs" in the game lit everything, even when none were nearby. "I'm assuming that this is the thing making the light, because if they are in caves, isn't it going to be a lot darker?"

Axel interpreted "cycle" as "this tells me the time, and it tells me it's a cycle old, so I guess spun around?" When asked for clarification on this comment in his debrief, Axel said he meant that he believed that days come from the Earth spinning, so a "cycle" in the asteroid must mean the same. He didn't think the time frame of a "day" in the game made sense, and that it went too fast to be realistic.

Sometimes players simply wanted a component to behave in a way that it could in real life. Bran was obsessed his entire session with disinfecting everything, as long as one germ was present, and was annoyed that he couldn't use the pitcher pump to clean itself. Kari wanted to

be able to build a ladder all the way to the ground in one area of her map, but a quirk with how a particular plant is programmed, she was not able to, and never understood why. The pepper plant she was building a ladder down toward actually takes up two vertical tiles, however it was visually rendered in its sprout form- so the tile above it was “filled” only because it was reserved for the plant to eventually grow into.

Jade felt that most aspects of the game seemed similar to how the real-world works, but noted gasses as the exception stating, “except perhaps when there's carbon dioxide over there it doesn't spread with no wall in between, it's a gas so it should move, but it doesn't.” This conflicted with her model that gasses move and mix. They do in fact move and mix in the game, but they can also separate, and Jade simply believed she should have seen more of that.

R3: Learning Game Design Recommendations

The third research question of this dissertation is “what are the design implications of the results of R1 and R2 for learning game designers?” The results of research questions 1 and 2 provide the basis for articulating recommendations for game design. The response to this question stems from the major themes of interpretation, and clear mental model changes (or lack thereof) observed in the data. It is important to note, games are complex multimedia environments, and designed digital learning spaces. Acute expertise in game design is beyond the scope of this question and this work, so these recommendations are broad. As a result, these results suggest that game developers that build learning games should consider design choices in the following areas, which the data demonstrated to be relevant.

There are two levels of response to this question. The most fundamental is in effect articulating several of the major themes within the findings as design challenges, and directing game developers to design solutions to the issues that these themes brought up. The second

level of response is providing examples for what a response to these design challenges could look like, building on critical examples from the data. These examples are used for illustration, and aren't necessarily the best solutions, as addressing them requires additional areas of expertise. Examples serve merely to support the results.

Design recommendations:

1. Develop ways to present quantitative information visually in the play space
2. Carefully design and test visual style and rendering of graphic assets
3. Design improved feedback systems players must encounter, and provide feedback to highlight both inefficiencies and failures
4. Integrate tutorials throughout gameplay
5. Provide a broader, linked information system and expanded dictionary

1. Develop ways to present quantitative information visually in the play space

Two superordinate themes in the interpretative results are that players used various forms of textual information, as well as visual information to make sense of what was occurring in the game space. An associated finding is a pattern of players to rely on graphics, visual cues, and objects in the environment to interpret it, as opposed to quantitative information and data tables that were readily available in many cases. Player understanding of phenomena in the game would have been enhanced had they recognized and internalized some of this quantitative information. While these findings are unique to this sample, it suggests that other players of similar games of a similar age might behave in the same manner.

One recommendation is to find additional ways to represent quantitative information in graphical form on screen with the players. Players often found the information overlay available in the game useful, even though they also often only relied on the visual component when

quantitative information was available there as well. Designers should consider ways to extend some of the aspects of the overlays that were effective and use them in the main play space. This would require a deeper understanding of dynamic data visualizations that can be programmed into the game. These visualizations would need to be tied to specific components, especially given the propensity of players to assign meaning to objects that occur near problems (proximal problem interpretation).

For example, in this game power wires could have been designed to exhibit a particular behavior when there is a large amount of excess capacity, or it is nearing overload. For example, if a wire is within 20% of its maximum threshold, perhaps it could turn yellow, and then turn red when it is overloaded. Much of the information that exists somewhere in the game in quantitative form could be presented in the primary play area in another form. Again, using the power system as an example, perhaps any time a player hovered over any wire or building in a circuit, a moderately sized bubble could emerge from the cursor showing a pie chart, with the size of the circle representing the overall load capacity of the circuit, and a wedge in the circle representing the amount of that capacity being used. Player might then more readily internalize, "building power generation makes the circle bigger, and the more things I put on this circuit, the more of that circle is used up". Small numbers representing the wattage of those pie slices could still be printed on them. However, providing an automatic visualization when interacting with that system, and having the primary method of communicating that capacity be visual could be more effective.

These sorts of graphic renderings and data visualizations could be used with any of the games' many systems. Perhaps hovering the mouse over any plumbing component could bring up a similar visualization in the shape of a liquid container, the size of which and amount it appears full being related to the quantity of clean water available to that system. Or as another example, perhaps with food systems, each time the player hovered over a component related to food production, some other graphic like a food box could be presented, with different levels

representing refrigerated food, a line for refrigeration capacity (if any), and the part of the visualization above the refrigerated line representing decaying food. Unrefrigerated food. Such an image could also show a deficit in food production or an excess in some visual form.

In summary, given that this sample of players relied so heavily on visual information, game designers should take this into account and design for it by making use of front-and-center visualizations immediately relevant to players.

2. Carefully design and test visual style and rendering of graphic assets

The particular visual style that this game was rendered in led several players to draw conclusions from scenarios that were not aligned with what was happening. The game features very stylized characters and graphics. The challenge here for game designers is creating a game that is visually coherent and engaging, while not sacrificing meaning or confusing players.

There is a tension here with game design principles. A common principle of game design is to use exaggerated graphical form to cue players as to what is relevant on the screen, and what they can interact with (called “active objects”), opposed to what they cannot (“background objects”). A common example is doors. A door that a player can go through in a game is typically more interesting, and a different shape and color than doors players cannot go through, so they stand out”. In a broad simulation game such as *Oxygen not Included*, because players can interact with everything, no particular components stand out. This is an information design challenge. The recommendation here is broad- think carefully about the art assets in the game, including animations, and consider cognitive testing of these assets to ensure that they don't cause confusion, or lead to unexpected interpretations.

Additionally, designers could consider ways to allow players to choose to filter graphics (and other information) on the screen for information relevant to a particular problem or current area of focus. For example, in the context of this game, if a player is struggling to generate enough oxygen, perhaps there is an "assist" menu that would change how information is

rendered to bring all aspects of oxygen generation to the fore. In this case, tooltips, data tables, and other textual information not related to solving an oxygen problem would be “greyed out”, while information specifically related to oxygen generation could be highlighted. Even the visual components themselves could be muted, for instance with the “oxygen assist” button pressed, anything not relevant to oxygen generation could be made 50% transparent on the screen. This would focus player attention on components relevant to the problem at hand, and allow them to avoid information overload, and could reduce proximal problem interpretation.

3. Design improved feedback systems players must encounter, and provide feedback to highlight both inefficiencies and failures

Numerous times during play, system design choices on the part of the player based on faulty assumption, or sometimes inattention, resulted in inefficient systems but we're not "game stopping". Much of the information that would have revealed this to players was quantitative in nature, which players very rarely interacted with, and was sometimes buried in data tables or unused overlays. Feedback is incredibly important in the experiential game-based learning model, which holds that some manner of feedback is required to prompt player reflection. Game designers should explore new ways to provide feedback to players, especially when players are not seeking it, and are unaware they should be seeking it. This presents another unique design challenge.

Once again, much of the information in this game is quantitative in nature and buried in data tables and overlays. The colony report contains some information that can be considered feedback, such as “power wasted”, but players rarely used it. No player ever noticed there was a field in the table showing how much energy was being wasted each cycle. A key type of textual information, alert texts, that appeared on the top left-hand side of the screen were sometimes used by players, but were ignored by players more often than not. And when players

did read this text, sometimes they did not seek a solution to whatever the alert was addressing. Finally, alert texts did not address every problem, and they did not address inefficiencies in player designs.

One potential design idea is to look at games that provide players regular feedback at the end of some time period, in an interstitial screen or animation between cycles (days). As a simple example, the farming simulation game *Stardew Valley* executes a cutscene at the end of each day with animations and text showing how much revenue the player made in each of several categories. In this particular game, and games like it in the future, designers could design similar automatic interstitial reports showing key information, maybe even some of the same automatic visual charts discussed above in recommendation one. An additional algorithm in the game could prioritize a "top three" area of focus to be presented in this interstitial screen, highlighting the space colonies three most pressing problems with both visual and quantitative information. In this way, periodically players' attention, for at least a few seconds, would automatically be shifted to a screen providing feedback. The most relevant feedback, in visual and quantitative form. (As an aside, this would also fix the day to night animation at the top of the screen, which confused so many players, but that is particular to this game).

Another solution would simply to increase the types of alert text to also account for inefficiencies, as well as areas of opportunity where players are not taking actions, and make the text larger, place it front and center, and require a player to click to make it go away. This would ensure players actually receive feedback and are aware of important information they might not otherwise engage with.

4. Integrate tutorials throughout gameplay

Most players in this sample did not interact with most tutorials, even though some of them are very rich with helpful information, and even display some information in creative visual ways. A recommendation for game designers is that they integrate tutorials periodically through play, in

effect making them required, as opposed to optional items at the top left of the screen (which were largely ignored by the youths in this sample). This might be especially useful for an impatient user population, or one that wishes for more “hand holding”.

The early phases of many games, especially complex strategy and simulation games, require players to complete a series of scaffolded tasks that build on one another, to teach players important processes and actions in the game. For example, the game *Civilization VI* has an “advisor” written into the narrative, that guides the player for many turns until they have executed actions within each major system of the game. (This system has a button that allows experienced players to shut it off). Oftentimes this scaffolded learning period is many minutes long and includes many actions. Designers of *Oxygen not Included* could use that strategy to require players to build an initial set of basic systems to get started. Thinking back to Hiram's second playthrough, he was able to get all of his basic colony requirements set up, except for food production, within the first 9 minutes of play. Designers of this game might have been able to create such a guided “soft introduction” that took about 15 minutes to complete, that would have left players with a stronger understanding of how to play the game, and a basic skeleton of systems to build on.

There are other potential approaches to this design challenge. Just as feedback can be fed to the player through interstitial screens, each time a player begins to build a new system, the game could simply cut away to a self-contained tutorial that explicitly directs the player to take a series of actions in a prototypical example of what they are working with, and ends when they have completed all of the steps correctly. This could cover anything from building a basic circuit, to establishing water pumps or a basic plumbing system, sanitation checkpoints, or address any of the other systems that players did not encounter in the game such as automation and logic gates.

5. Provide a broader, linked information system and encyclopedia

The final recommendation is to link all the major components in the immediate user interface with relevant information. This could occur in multiple ways. First, tooltips would include hyperlinks to relevant data tables that are buried deeper in the game. This would require an additional input action to make the tooltip “sticky” and clickable but could provide an easier route to a centralized piece of information about a system. For example, a player might hover over a component such as a building and see a tooltip that features its temperature, and then be able to click on that temperature to pull in all of the data impacting that component attribute, such as specific heat, major sources of internal and external heat transfer, any heat the component is generating, etc. And once again, this information can be displayed in a predominantly visual form, but also include the quantitative information alongside it. Players may be more likely to interact and dig deeper into phenomena if the information was more accessible, both in the user interface as well as cognitively accessible through visualization, or simply more interesting to look at.

A final way to provide players with information is to provide a dictionary the players could refer to anytime. *Oxygen not Included* does have a help menu, called the “Database”, but no players used it. It is accessible by clicking a single small box on the top right of the screen and does have information pertaining to many of the game components. Expanding this, making it more visually accessible, and adding a dictionary to explain every term in the game such as “consumable”, “hypothermia”, and “metamorphic rock” (some of the terms players struggled with), would have provided a means for players to get definitions for words they didn’t know quickly and easily. This could be added to the “linking” system so that players could open a definition for any unknown term right from the tooltip.

Chapter 5: Discussion

Unbracketing Theory

The work was exploratory in nature, and was intended to discover and describe interpretative themes, as well as measure to what extent player mental models shifted when playing the game as supported by these interpretations. However, it is critical to review the results of this study and compare the results with existing theory to determine the extent to which theory and results are aligned. Extending the analysis into a discussion of how it connects to relevant theory shifts the discussion from an isolated evaluation of gameplay experiences within a single game and situates the results among prior work and relevant research constructs in order to extend scholarly discussion in the domain.

The requirements of IPA state that theoretical frameworks should be bracketed and set aside during data collection and analysis. Consistent with a Heideggerian approach to phenomenology, with analysis complete, theories and frameworks can now be unbracketed and used as a lens to examine and discuss the results of the study. As discussed in Chapter 2, experiential game-based learning was the core theory that informed this work, and the preponderance of discussion about theory will engage EGBL theory. However, the results are also relevant for two frameworks referenced in Chapter 2: Gee's 16 Principles of Good Video Game Based Learning, and Resonant Games framework developed by the Education Arcade at MIT.

Study Results and Theory

The broad picture painted by these results, when compared to the assumptions and predictions of theory, reveal that there are significant gaps in the ability of theory to account for

the gameplay experiences. When the results are examined in parallel with existing theory, it is inadequate to explain beyond broad themes, the manner in which players made meaning of the game space and does not fully align with the way players learned as they worked their way through challenges. The assumptions of the theory and frameworks that informed this research are limited in their ability to explain game-based learning behaviors consistently, in this particular sample and this game.

This experience with these players reveals that even a game that is carefully designed by an experienced developer, to model real world phenomena with a high degree of representational congruence, produces mixed results. With regard to R2, a little more than half the time (57%) continued gameplay eventually resulted in a mental model shift from a differing or unknown state to an aligned model. In 43% of the observed critical incidents, they did not. These results only speak to this sample, which was drawn from middle school learners, there remains nothing in the major theories discussed that qualifies or differentiates how they might play out with different demographics.

Experiential Game Based Learning

The assumptions of experiential game-based learning (Kiili, 2005) were adopted and for this research (fig. 2). This approach assumed that problems players face in *Oxygen not Included* would form the core ("beating heart") of the player experience, and that through the process of play and idea generation, players would learn. This assumption appears to align with EGBL theory at the highest level and is consistent with the core element of the EGBL model, as the problems in the game space overwhelmingly drove player behaviors and thinking. The theme of this game is survival in an asteroid in outer space, and the challenges the game presents to players pertain to developing life support systems for characters, driving the primary problems the players must address, and providing narrative context for the game. It is evident throughout the data that for the most part, players were preoccupied with short-term goals of solving

problems and addressing challenges related to atmosphere, power, food production, environmental regulation, and other areas related to STEM concepts.

Revisiting the theory, we can review the two loops that emerge from the experiential game-based learning model in light of the results. The first is the pair of idea generation loops that feed into learning goals. This loop of the theory assumes that players will be forced to generate ideas based on their existing knowledge and knowledge available in the game, to address the problems, leading to learning. Many of the behaviors and critical incidents discussed in the analysis are also consistent with this idea. Kiili states “after the preinvasive phase a player further develops solutions by considering the constraints and available resources of the game world”. (p.18) There are many instances in the data where it is clear players considered constraints and available resources, for instance players understanding a power capacity or space limit, perusing available buildings to construct, or even considering literal resource constraints such as limited water or metal. However, this is where the path proposed in the theory begins to diverge from many observations of participants. In many instances, players did not fully engage this phase. In some instances, players did not consider (or were not even aware) of potential resources such as specific materials or buildings. Players did not always notice resource constraints, or capacity limitations. Players might be motivated to solve the problem, but not develop solutions “by considering the constraints and available resources”. In many cases other approaches were taken such as taking random actions or failing to internalize that a solvable problem could be tackled such as Letty eventually ignoring hypothermic characters.

In instances where players did in fact move through the preinvasive idea generation phase, and fully engage the idea generation phase to fully consider constraints and resources in the service of addressing a challenge, players did often show evidence of drawing from existing knowledge, or alternatively learned new things about gases, power management, materials, and other domains to solve problems. These instances are consistent with the ideal path laid out by

EGBL theory, and there were numerous critical incidents where players were forced into a situation where they were required to gain an understanding about something new to solve a challenge. This satisfactorily matches the EGBL loop feeding back into learning objectives. However, there were also numerous critical incidents that differed from this aspect of the EGBL model. The simplest deviations to understand are simply those cases when players failed to solve a challenge before the end of the play session, or ignored a problem, and learning automatically did not occur by default.

A more complex pattern of deviation are the numerous instances where players were able to solve problems and maintain a mental model that differs from the real world or were simply unaware of why something worked and continued to communicate a model that differed from reality. EGBL does not account for a range of activities beyond what is expected (active experimentation) into unexpected behaviors (random or accidental actions) that players employ to address a challenge. EGBL as written implies that this happens very often. However, in this sample with this game it was fairly common, as 48 out of 115 cases never ended up shifting even though there was an opportunity for it to happen, often even when other players of the game made the same shift in their playthrough. In effect, the emergence of a challenge or solving a problem was no guarantee that a shift in mental model occurred from where it differed before. Many of the ideas that players developed were based on faulty assumptions, and even when players chose a workable action, it did not necessarily result in a shift and therefore learning. When looking at these results through the lens of EGBL, the preinvasive idea generation and idea generation loops then seem more like “possibility paths” that potentially lead to learning, which takes place sometimes, but are not guaranteed.

The second loop in the EGBL model assumes players go through a cycle that supports learning through reflection. With “clear goals” coming from the beating heart of the model, (challenges), they direct players toward active experimentation. Within this sample, the “clear goals” that initiate the sequence were activated at some time and not others. Most of the time

the goals appeared clear to players in the data, such as players needing more food production, oxygen needed to be replenished, or a system needed power. However sometimes goals were not clear, and this could be due either to expressed uncertainty on the part of the player of "what to do", and at other times due to players creating a goal for themselves generated not from a genuine need driven by the game state, but their own perception based on the interpretation of the game through their individual lens. At a first look, this may appear to be solely a design issue with the game, but a large amount of the "unclear goals" stemmed directly from interpretive themes unique to individual players as discussed in R1. For example, players reacting with outsized allocation of time and resources to cleaning germs, or interpreting specific graphic assets as having more meaning than they did. That said, there were also instances where players took actions that must have stemmed from unclear goals, such as building additional power production capacity when none was necessary and building extra components such as batteries or ventilation systems when not needed come to mind. Unclear goals led players to solve problems that didn't exist, and on the other hand ignore problems that persisted. There also seems to be a tension between providing players an open world and range of possible solutions to solve problems and establishing "clear goals".

Thinking through the next node in the experiential arc of the EGBL model, "feedback" from the game leading to reflective observation on the part of the player is assumed to occur from the results of active experimentation. Again, this is a process that occurred in this sample some of the time, but not all the time. In the examples mentioned in the previous paragraph, and in numerous other cases, a lack of immediate feedback caused the players to continue to maintain their assumptions. Bran's characters were certainly not getting sick due to so much cleaning, and his cleaning was excessive, but there is no feedback in the game that would have alerted him to his outsized reaction to the visual presence of a few germs on the screen and ignoring all other information. Similarly, there is no obvious feedback in this game given when power capacity is in excess of the total of all system needs. The fact that "too much" continued

to work in most situations, with no feedback, in some sense short circuited the experiential loop in those specific scenarios. There are certainly plenty of situations it did not, such as when Fern had wires melt and a circuit short due to too much power on a line that could not hold it, or when over pumping gas in a chamber maxed out its pressure or popped character eardrums. The experiences players reflected on the most were the ones they were forced to, when a critical system seemed to be impaired. As long as things appeared to work, even when executed very inefficiently, reflection was limited. In the absence of feedback, there was no basis of reflection unless something, broadly speaking, "broke". The specific nuance not included in EGBL is this threshold for reflection.

The next piece of the experiential loop links reflective observation to schema construction, linked in part by the focused attention of the player on the game, and usability. In this work, schema construction has been discussed interchangeably with the concept of mental models. Once again, the analysis shows that when players understand a clear problem, it is possible for them to focus their attention on it, and often the usability of a game supports a shift in player mental model in the direction more aligned with the real world. After this point, the loop is closed back with the beating heart of challenges in the game as "control over game skills advances", and the model assumes learning has occurred. However as noted earlier, this loop can fall apart if the feedback action and reflective observation actions collapse or don't take place. The data are again partly consistent with this, as player schema did not change, and skills in the game did not increase when these steps didn't take place. There is a subset of incidents throughout the data with players failing to receive, or internalize or understand feedback, and therefore failing to reflect on it.

There is also something to unpack relating to the usability node in this model, as aligned interpretation is one goal of the usability of the system. The contrast during play sessions between an outright system failure versus a more circumscribed inefficiency that happened not to be game stopping was very clear. Gee (2008), notes that an explicit goal of learning game

design is that games should contain robust and continuous feedback, which is in line with this conclusion. Gee also notes a related principle, that games are designed to allow people to “fail safely”, and in failures there is learning. More direct and explicit feedback about inefficiencies is a recommendation noted in the response to research question three. So, while this nuance is missed in EGBL, Gee’s framework addresses it.

The final piece of the experiential game-based learning model is the idea that when these cycles are completed at the right level of challenge for a player, the loop runs more efficiently, and the state of flow is achieved. There is some evidence in the data that is consistent with this idea. The three players with the least experience all struggled to achieve basic goals in the game, and had the strongest opinions about the difficulty of the game. Letty said the game was incredibly challenging, Darren said it was hard, and Emery said she found it difficult. Both Emery and Darren expressed a significant amount of frustration, with Darren’s loudest statement being a very frustrated “tell me what to do!”, and Emery saying that the game felt “very frustrating”. These three players also happen to be three of the four players that made the least progress during their sessions and were the players with the least experience. Csíkszentmihályi’s flow theory posits that given the lower skill of these players, they would be the least likely to attain a state of flow, and have less focused attention, and feel a lack of control over the situation. While this represents a limited number of participants, this very strongly appears to be what happened. Statements about frustration or boredom and lack of focused attention were not measured using these methods. However, these three players recorded some of the shorter playing times and were eager to end their session. These data cannot show whether this represents disinterest in games in general or stemmed from the lack of focused attention and interest that would have been achieved by flow had their skill level matched the challenges of the game. The results are at least consistent with the EGBL model.

This observation in the data is also consistent with prior work. For example, Warren et al. (2012) noted that many students are not prepared to learn through games due to lack of

experience with the medium, and Mawdesley et. al. (2011) simulation game-based learning exercises are not suitable for all learners and describe the need for additional work to expand the affordances of this medium to more learners. Despite these experiences, it is worth noting that there were instances for each of these inexperienced players where they had a schema shift toward more alignment with the real world. On the other side of the coin, players who seemed to navigate the game very well such as Isaac and Hiram also had a high level of game experience and seemed to work relatively quickly in the game and did not express frustration at the game at any time consistent with EGBL and this prior work.

Mental Model Shifts

During data analysis, 114 critical incidents were highlighted that pertained to shifts in player mental models. There were 66 shifts from an “unknown” or “differs” position to an “aligned” model. Broadly speaking, this represents about 5.5 shifts toward alignment per participant, ranging from 19 (Fern) to 3 (Emery). Across the entire sample, this equates to about once every 19 minutes. There were 48 critical incidents where a player's position about a concept did not shift from “differs” or “unknown” to “aligns”. This equates to about 4 “missed opportunities” per player. Again, these results are specific to this sample and this game, are not intended to be statistically representative of any type of experience, and are presented here solely for the purpose of discussion.

It is difficult to assign an overall value judgement to the relative rate of mental models shifts in this experience. On the one hand, these data demonstrate that games can indeed result in players experiencing in-game phenomena, and shifting their understanding of STEM concepts and systems. On the other hand, there were still a substantial number of cases where a player did not experience a shift. Additionally, there were many instances where circumstances and elements of the game itself actively interfered with interpretation,

contributing to a different conceptual understanding. Ultimately, there was more shift toward alignment.

It is also important to note that describing these critical incidents addresses an important but narrow conception of what player learning took place. An observed change from an unknown or differing mental model to an aligned model, justified by clear verbal mediation, is only one potential measure of learning. As a reminder, learning is assumed to be a knowledge or behavior change as the result of experience. (Kolb, 1984; Mazer, 1986) What is significantly more difficult to measure is the “inchoate” knowledge described by Arena & Schwartz (2003), “in experiential learning, students develop intuitions that are likely to be tacit and inchoate. They are important experiences, but they may not have the verbal mediation that translates into answering abstract or general questions”. With this in mind, it follows that players may have internalized some “tacit and inchoate” forms of knowledge in the game system that did not translate via verbal mediation into think-aloud data. This particular study did not detect all of the mental resources acquired that a player could potentially draw on in the future. These middle school participants in this study have likely developed intuitions that may not easily translate into material that could have been articulated in a think-aloud statement or prompt, perhaps even about incidents where their understanding still differed from the real world.

The concepts and ideas encountered in the game may emerge later in other players’ life, and the player might still reflect back on them. The very same participant who started and ended with a misaligned concept in this study, during play may still have acquired what Danielsson & Selander (2021) term “semiotic resources”, that when activated later could actually help facilitate learning. For example, the players that came away from this experience with a different or unaligned mental model for what a “pneumatic door” is and how it works, may later encounter the pneumatic concept again in another context, which stimulates recall of the experience. In this case, the player might then reflect anew back on the gameplay experience and how the game components behaved, and with this new context and reflection, the prior

experience (and “semiotic resource”) may actually reinforce the new learning. Scholars have posited that different types of semiotic resources provide different “affordances” for different types of meaning making (Gibson 1977; Kress 2003, Danielsson & Selander, 2021), and the symbols and systems that compose a game model have their own affordances for “meaning-making potential”. The formal components and their relationships in a game form a set of semiotic resources that can be modeled after real world phenomena that the players encounter while playing. There is no “expiration date” beyond memory decay for experiences, and the ability to reflect on them, though both these results as well as prior work suggest learners may require guidance to use the resources. Danielsson & Selander (2021) note, “from an educational perspective, it is a great asset to have an abundance of semiotic resources to choose from when engaging in various aspects of content” (p.17), but also warn “we cannot take it for granted that the students will be able to handle the different resources without guidance, or to be able to see their possibilities and limitations”. (p.17)

Reflection and Scaffolding

Expanding on the idea of guidance and post-play reflection, some scholars suggest that guidance is useful to maximize game-based learning (e.g. Zapata-Rivera & Greer, 2003; Mawdesley et. al. 2011; Kori et. al. 2014). For example, Moreno & Mayer (2005) conducted three experiments that concluded guidance and reflection after playing a STEM themed game resulted in higher post-activity test scores. Interestingly, Foster & Shah (2015) use a mixed methods approach to review the effectiveness of the Play Curricular activity Reflection Discussion (PCaRD) model, which involves game play, followed by a reflection discussion. Their interpretive analysis suggested the approach aided student learning, however their quantitative measures on assessments were mixed, with the only statistically significant gains being in math. Illustrating the vexing problem of inconsistent results in areas of game-based learning, ter Vrugte et. al. (2015) detected an increase in student math ability after playing a

math learning game but did not detect any difference in learning outcomes between groups with and without guided reflection. While there appears to be significant support for guidance and post-play reflection, other scholars have found no difference between outcomes on learning measures between a test group that had a post play reflection and those that did not (Cowley et. al., 2013). Why reflection appears to work most of the time, but sometimes appears ineffective, is entirely unclear and once again cannot be accounted for by existing theory.

On the other hand, Bransford & Schwartz (1999), who also studied games, pose a counter view. They ask rhetorically, “since novices will often generate ideas that are incorrect, they must eventually be guided toward more fruitful ways of thinking why not “cut to the chase” and present the correct ideas right from the start?” (p.78) They directly tie the need for participants to struggle with interpretation of phenomena on their own first through the lens of preparation for future learning, “the PFL perspective suggests a number of reasons for first having students generate their own ideas about phenomena”. (p.79) The first reason is that it provides opportunities for learners to contrast their thinking with experts (“aligned” views) and “set the stage for appreciating the critical features of the new information”. (p.79) The new information is then appreciated beyond a set of facts to be learned. Second, it pushes against learner “overreliance on assimilation”, as it allows learners to experience firsthand that repeating old information and old assumptions in new situations can fail, to “resist making old responses by simply assimilating new information to their existing concepts or schemas”. (p.80) The game experience can actively halt and counter negative transfer.

Inadequacy of Theory

Tying these ideas together, EGBL theory does not account for PFL, an attribute critical to games-based learning as noted by such scholars as Gee’s & Bransford & Schwartz’. Collectively, the notion expressed in the previous section that while in this study some players ended the game with a misaligned idea the experience may prove useful in the future, and the

assertion by Bransford & Schwartz and aligned scholars that this type of experience is still useful, underscore the importance of incorporating PFL into any games-based learning model. As it stands, there is no “loop” coming about of the EGLBL model to account for this, nor is it possible to have measured that in this study.

It may simply be the case that designing a unified theory that describes and explains game-based learning with some higher level of accuracy and in a higher level of detail, and maps more consistent patterns is not possible. The three spheres of EGLBL, PFL (taken as a principle or theory), and “design principles” for game-based learning remain largely siloed. There are robust references to each in scholarship, and some points of each intersect, however they each have different foci and scope.

It also may be the case that games are too complex to rely on one model or framework for understanding. An apt comparison might be museums. Asking “how do people learn in museums?” is simply too broad a question, as museums and what they offer vary so much, so models have been created to decompose these environments down into specific elements and apply narrower theories and frameworks to those. A better approach might be to begin designing some sort of Contextual Model of Games Based Learning, following in the footsteps of Falk & Dierking. The Contextual Model of Learning (Falk & Dierking, 2004) defines a learning space using eight factors within three overlapping contexts (personal, physical, sociocultural) for any experience. Maybe understanding the “game context” in terms of specific forms, patterns, design elements, and affordances and focusing future theory on describing narrow behaviors within the in-game context would be a more fruitful approach. Future work that explores interpretation and mental model adjustment in games may then focus on specific contextual and design factors. What this might look like can vary, but it brings the individual learner and sociocontextual factors into the learning framework. The observations in this study are consistent with the idea that experience playing video games is a factor that impacts interpretation. Age and education level are certainly others. These could be factors that define the “personal

context” characteristics of a game player. This, along with the combination of some sort of mapping for “in-game context” (form and design of the in-game environment), as well as sociocultural contexts (is it a solo or multiplayer game? Is there facilitation or guided reflection?) may then produce a framework that can map research findings at a more granular level, with more predictable results given a set of contexts and factors.

IPA as Game Learning Research Approach

This work used interpretative phenomenological analysis as its primary approach, which has been adopted from psychology to study player understanding of games, as well as learning. In this study, the phenomena in question were in a game environment, and the complex intersecting systems with which participants played standing in as models for real world STEM phenomena. Previously, the IPA approach has independently been used to study gameplay and has separately been used in conjunction with think-aloud interview techniques in non-game domains. The findings of this study represent an original contribution to the literature, as a first effort at combining these techniques to understand how a set of middle school players made meaning in the game, and how their understanding shifted in real time. The supplementary method of formal analysis and description provides a controlled structure language to describe behaviors and discrete gameplay primitives.

Two of the superordinate IPA themes and their subordinate themes represent themes that focus on information explicitly integrated into the game space, textual interpretation, and visual interpretation. These two themes were somewhat unique when compared to other studies using IPA, as they are narrower and less abstract than many themes that often appear in research conducted with this approach. However, interpretation even of information intended to be explicit and unambiguous was subject to variation in use and interpretation in this sample due to individual differences. A third theme, real world models, described how players used their

understanding of real-world systems to interpret behavior in the game. The IPA commitment to ideography became more salient with this theme, as there was a range of understanding of these systems, and players came to the game with varying schema. This was the purpose of choosing middle school learners attending schools that use NGSS science standards, as the content in this game closely matches standards at about this grade range. Indeed, players had many common understandings about the STEM content in the game, but enough individual differences in schema that as players revealed their mental models, differences were communicated and apparent.

Studies conducted with IPA typically have small sample sizes, and that was the case with this study. The results are unique to this sample and this set of unique youths, however the findings of this work shed light on the types of themes that might be typical and provide areas of focus for future work. The results of this study are not generalizable in a statistical sense, though as games and learning scholar Gee states “there are patterns” that can emerge in game-based learning, and these findings shed light on areas for closer examination.

Using a think-aloud interviewing technique in conjunction with IPA provided a great deal of information as to how players were interpreting the game space. Still, the data represent only a fraction of what a game player is thinking and interpreting, and the limits of what a player chooses to say. It was helpful sharing a common view of the game when collecting data, as I was able to see the player act on objects and make decisions, and very frequently prompted the players with questions like “why did you do this” and “what does that mean”, and all the other questions in Appendix C. This helped capture additional statements on what the player thought, and their interpretation.

Using IPA as a research approach was useful for gaining an understanding of how participants interpreted objects and events, and future researchers might wish to consider this approach. The most significant challenge of this approach is that data analysis is very time consuming, and combining think-aloud interview transcript, along with notes about player

actions at a fine level of detail is very time consuming. Researchers who are willing to work with small sample sizes could be well served using this method if the information they are after is related to participant meaning making of game systems. The types of insights it provided in this study may also surface in future work, tying specific player beliefs and ideas about what components are, and how systems work to prior knowledge (existing schema). Researchers may find rich and specific information about player models and ideas about the phenomena in question. It appears likely that the more complex that a game or experience is, in terms of the number of components, attributes, relationships, and systems, the more opportunities a player will have to share interpretations. Researchers who are studying a game or system with a narrow focus, and fewer components or systems, might not be as well served by using IPA, as other approaches may be more targeted and efficient.

Implications to Game Form and Design

This work sought to explore and explain player descriptions of the game, and the game space in terms of its formal composition. In games-based learning literature, the game itself is described on a number of levels. In many projects, the game is discussed in general terms, themes, and broad strokes. For example, Arena & Schwartz (2013) describe the content of the scenario in general terms, comparing it to *Space Invaders*, and the data collection and analysis don't require deeper understanding. Other work such as Plass (2012) and Horstman (2013) go into more detail linking specific actions and statements to specific formal components of the game.

Combining an interpretative phenomenological analysis approach and focusing on organizing the analysis and formal terms provided a unique angle for looking at specific player behaviors and describing them in the structured manner. One way this came across in the study was that it highlighted the boundaries (or discretization) of components in the game. It highlighted how players understood and interacted with these individual components and their

relationships with one another, but it also shed some light on the boundary at the edge of what a model is capable of, and how this can impact player understanding of the game. The analysis of this game described how player interpretation was impacted by the formal game components and systems. It appears this itself took place on two levels. The first was with specific components and how they were represented, and the second was about their behaviors (both player and system actions).

With regard to specific components, examples brought up in the analysis include a player believing that carbon dioxide could be converted to oxygen because of the way the components toggled, a player believing that a component of air trapped between a rock in the water indicated that there was dissolved oxygen in it, and a player believing a plant and rock were combined due to how they were rendered. The prototypical examples used to support and to describe this in the results, and mentioned here, are a very small subset of the types of interpretations that took place.

As a thought experiment, one might consider one of these critical incidents and see how interpretation might have changed had particular models been represented in different forms. In this particular game, the play space is divided into discrete units, "tiles". Each component is an instantiation of a class of components, each type of component having specific fixed attributes (e.g. hardness) and adjustable variables (e.g. temperature). Even gases are discretized this way and represented as tile shaped components (visible on tooltip, and in the atmosphere overlay). This choice of form had numerous direct consequences to interpretation across most players, and their understanding of the phenomena and models they were intended to represent.

One might imagine gas is represented in a different form. Rather than individual tiles, gases could be represented as larger contiguous units of space. The physical space of a gas-filled chamber would not change, for instance, but how the gases are represented in that space could be altered. The chamber and all its tiles become a contiguous component as it changes as players expand or contract it. Then that component itself would have different variables

representing the amount of each gas in that space, their masses and temperatures, and an array captures abstract units of gas that enter and leave the space. The attributes of that component would change through system actions. The entire chamber could have several pieces of information such as the amount of each gas, temperature, and even an abstract number representing differentiation of gases based on other attributes in the array. Simply put, a contiguous unit of gas filled space could be programmed to behave like a single component with dynamic attributes representing mixed gases.

With gases represented in this form, player interpretation would surely have been different in some of the critical incidents. Celeste's interpretation that carbon dioxide was being converted to oxygen because of rapidly toggling gas component tiles could not have occurred. The players that expressed extreme reactions at a few components of carbon dioxide such as Fern, Darren, and Emery, and interpreted the situation as more dangerous than it was, may have had more tempered reactions to such a representation. In some cases, it may have mitigated the primacy of a visual effect over the value of the quantitative attribute it reflected.

As outlined in the results to question three, the implication of this work with the sample is that formal representation should be strongly considered by game designers, and future work could potentially explore multiple forms of representation to see how player interpretations change. This can have a direct impact on whether a player comes away with an aligned or misaligned model.

Implications for Games as a Literacy

These data and conclusions, particularly those within the “game mediated interpretation” superordinate theme, are consistent with the idea that video games represent their own form of media literacy, and that being “game literate” impacts the ability of people to learn from games.

This can be discussed on two levels. First, video games have their own “literacy” with games and gameplay in general, and have ways of being read (Bogost 2008; Squire, 2008; Steinkhueler, 2007). Second, there is the idea that game players learn and re-apply many game specific concepts, such as formal structures, gameplay patterns, terminology, actions, mechanics, and even cultural concepts that are unique to interpreting games. Salen (2008) states, “to “read” a game system in order to play with it points toward a specific kind of gaming literacy connected, in part, to the ability of a player to understand how systems operate, and how they can be transformed”. (p.8) In this study, game comparisons and assumptions informed players’ expected behavior of the game and meaning making within it and led to the re-application of knowledge from game patterns or other specific games this new one. This appears to be a novel finding. As previously discussed, there were also clear differences in gameplay and interpretation patterns between the three players with “little to no” game experience, and players with more experience, consistent with this idea.

Bogost (2008) connects “learning to play games” with the ability to interrogate the models in games, “playing video games is a kind of literacy. Not the literacy that helps us read books or write term papers, but the kind of literacy that helps us make or critique the systems we live in. When we learn to play games with an eye toward uncovering their procedural rhetorics, we learn to ask questions about the models such games present” (Bogost, 2008, p.136). Endorsing the idea of video games as a literacy, Steinkuehler even more closely ties gaming literacy to meaning making in games, as the ability to “recognize and produce meanings in a given semiotic domain, with particular attention given to sense making in multimodal, multimedia spaces such as those enabled by digital technologies”. Exploring an aspect of how this occurs was at the core of this work. And in some sense, these results represent one small response to Steinkuehler’s “surprisingly lack of research on what kids actually *do* when they game” (emphasis hers). These statements were about her work with massively multiplayer games, and the learning taking place from the “doing” in those games. This work takes this idea

in another direction for another set of “doing” in another type of game, seeking to explore player interactions and interpretations in fine detail.

An implication of these findings, situated in this perspective, is that developing a gaming literacy can help learners maximize their learning in a game environment. Buckingham & Burn (2007) make the explicit point, “if we intend to teach through educational media, we also have to teach about those media”. (p.323) In the service of preparing learners to use video games as a medium, they say “teachers might teach about computer games as a medium in their own right, just as they teach about film or television or literature” (p.323) This is a strong case for accounting for game literacy in formal education- game studies should be a part of formal education, as an aspect of media literacy. This would also address the concerns of other scholars who have identified this need through their work in game-based learning experimentation (see Hunicke et. al., 2006; Mawdesley et. al, 2011; Warren et. al. 2012; Costa et. al. 2018) Some scholars even suggest professional development in game-based learning for educators (Ketelhut & Schifter, 2011; Easterling, 2021).

A final implication stemming from this idea pertains to the growth of the learning games market, as referenced in Chapter 1. Learners who have not experienced or practiced many games will be at a systemic disadvantage in the future, if futurist educators longing to integrate more game-based learning in classrooms get their wish. Formally developing a gaming literacy will be indispensable in such a world.

The notion of game metadata containing elements that classify some formal systems of games is necessary to the concept of games as a literacy. This is especially true if some future contextual model of game-based learning requires controlled descriptive elements to describe its in-game features. A mature media should have a means of formal analysis to facilitate the development of literacy in that domain, and the elements and vocabulary to accompany it. These elements can be classified and related in schema. Art can be used as an example. As discussed in Chapter 2, in the early 20th century art was the first visual media to be

decomposed into formal elements in the modern sense, and other media followed. Fry stated, “the goal of a formal analysis is to explain how the formal elements of a work of art affect the representation of the subject matter and expressive content”. Then, the goal of a game formal analysis could be to “explain how the formal elements of a game affect the representation of the subject matter and expressive content”. This resource goes on to list the traditional elements of art design in specific art media, such as “line”, “composition”, “color” and even child terms such as (under the parent term “color”), “hue”, “value”, “saturation”, “intensity”, etc. There are already controlled vocabularies and taxonomies for this purpose, such as the Getty Vocabularies, and Categories for the Descriptions of Works of Art (CDWA) schema. There are also efforts at creating game taxonomies and controlled vocabularies (Lee et. al, 2013). This research has implications for future work on video game metadata.

Implications for Game Metadata

By definition, the design of a game is composed of its formal elements, some of which are described in various game metadata schemas (Lee et. al 2013, Hendrix et. al., 2012, Fukuda & Mihara, 2017). Over time, video game players have generated a folksonomic and semi-technical language that form a specialized language video game players use to describe various aspects of the design. These efforts and creating metadata schema have attempted to control these terms. Reflecting on formal terminology, whether fine arts, Russian fairy tales, or video games, these efforts at formal analysis and associated vocabularies are integrated with various taxonomic efforts. Within the last decade, several efforts have been made to develop metadata schemas and controlled vocabularies to describe aspects of video games, some of which relate to, or are identical to, primitives and elements in formal design such as those described by Lankoski & Bjork (2015), and Zagal & Mateas (2007). These data from this sample show that the form of how information is represented impacts how it might be interpreted by players, and

how it can even be counterproductive in a learning game. There are implications of these findings to the future development of these metadata schemas and taxonomies for games.

With regard to the connection between formal analysis of games and game metadata, examples from the data and previous discussion described the need to be able to describe form for context, as well as the finding that various formal components impact player interpretation of the models they represent. For example, this work described the consequences of discretizing space in this game into squares, and displaying it as a 2D grid, to compose the framework of the models in the game. The Video Game Metadata Schema 4.1 (VGMS) describes these properties in the “perspective” and “point of view” elements. Other elements that impacted interpretation can be noted. The mechanics element of video games also has a strong relationship to the actions primitive in formal representation. The “mechanics” element in schemas are in fact tightly related to fundamental actions in the game such as moving, collecting, resource use, etc. Even gameplay genre is an aspect of games tied to the action primitives of a game, with many gameplay genres listing the primary actions (for mechanics) as a defining characteristic, such as “shooter”, or “social simulation”. Even the time formal element games as described by Zagal & Mateas (2007) is included in some form in some schema, such as the VGMS, and is also related to gameplay genre as an element included in some of the names such as “real time strategy”.

A superordinate theme in this work is visual representation, with a subordinate theme of graphical form and weighting visual phenomena. The visual style metadata elements have a relationship to how components are represented, which is given added salience in light of the visual interpretation themes in this sample. The art style of the game is “stylized” according to the “visual style” controlled vocabulary of the VGMS, which is noteworthy as players interpreted some of the stylized facial expressions of the characters, and their silly animations as significant, and meaning specific things they were not intended to. Appendix B describes the

game *Oxygen not Included*, and the main STEM systems it models, and includes a table of information classifying many elements using the Video Game Metadata Schema.

The implications for metadata development are threefold. First, future games and learning research may focus on examining how games representing the same knowledge modeled in different perspectives, visual styles, mechanics, and other elements differ in how they are interpreted, or in some other measure of learning outcome. The subset of elements in a game schema that have a one-to-one relationship between these discernible formal items can be used to ensure that elements which could be relevant to a learning research use-case are included. Second, this strengthens the need for and games and learning, games and education specific subset of terms (controlled vocabularies). Third, these terms would then have a relationship to some existing and potential future metadata schemas. The VGMS has already been discussed, however there are other approaches that address learning game and serious game taxonomy. Hendrix et. al. (2012) defined what a metadata schema for games as learning objects should address and built a four dimensional framework articulating the categories of “learner specifics”, “pedagogy”, “context”, and “representation” information classification needs for games. Game form and style elements are addressed in the “representation” dimension, engaging “how active the learning experience needs to be, what levels of fidelity are required and how immersive the experience needs to be”. (p.15) However in its current form the terms are very broad, and future work could expand this area. Hendrix et. al. have proposed expanding the IEEE Learning Object Metadata (LOM) standard to include such classification elements. (IEEE, 2021) There are a vast number of ways that games have been and could be designed to model physical and social phenomena, and linking formal terms to metadata schema provides a basis and structured language for controlled comparisons in research.

Taxonomies and formal definitions are both sets of controlled terms, and with shared understanding can also provide the basis of concrete exploration of how ideas rendered (or represented) in different forms in games can be researched and compared. Many questions can

arise from this. For example, does switching from a cartoon visual style to a realistic, or even more abstracted pixelated style change how much weighting is given to visual imagery, and affect interpretation and learning outcome? Does rendering the same physical concept into a different dimensionality impact these things? How does modeling a phenomenon using different mechanics change interpretation? Does swapping out a game mechanic that replaces a quantitative strategic mechanic with a qualitative kinetic mechanic lead more often to an aligned interpretation, or change learning outcome? There are a few scholars who have taken this comparative experimental approach (e.g., Plass et. al., 2012), but when games for learning are used in research, usually the game itself is the experimental treatment, not different versions of the game. Mayer (2016) has called for more of this type of research, though this body of work remains relatively small.

Future Research

This discussion has already introduced several potential areas for future work, such as testing the same concepts represented with different design elements and developing metadata and classification systems of formal elements. The methodology employed in this research—using interpretative phenomenological analysis approach, in conjunction with think-aloud gameplay interviewing, and analysis structured with a formal method is a tripartite pattern that could be repeated to explore player meaning making of other games at a more “granular” level, as described by Deterding (2011). Maintaining this pattern with different subjects and different games would allow for various comparisons and develop a body of interpretative work. It could also potentially begin to map some sort of context specific results.

This work focused on the gameplay experiences of twelve middle school aged youth, and involved play in one game, in gameplay sessions that averaged roughly an hour and a half

in length. This sample is typical using an IPA approach but remains small. A future study could adopt this methodology with another age group, even using *Oxygen not Included*, to see what changes in interpretive themes might emerge. This set of participants only experienced early systems in the game, and older players that bring a different level of understanding to the game would likely encounter the more complex systems modeled in the game. Similarly, a researcher could focus on exploring differences in learning between “experienced” players and inexperienced and more concretely test for interpretive or learning measure differences on that dimension.

Future research could also seek to work longer and go “deeper” into the game with a smaller number of participants. Would interpretative patterns change after many hours of gameplay? Would participant progress accelerate, and would they encounter more of the vast knowledge designed into the game model? Would pre-building specific scenarios with the game’s world design tools serve as a streamlined approach? There are plenty of ways to iterate on this study specifically.

Conclusions

This work used the approach of interpretative phenomenological analysis and think-aloud interviewing to explore how a sample of middle school learners make meaning from game systems as composed by formal elements representing real world STEM knowledge. It also explored how player mental models of real-world concepts shifted during play as they experienced the game space and interpreted what was taking place.

This work resulted in four superordinate themes, with 11 subordinate themes (table 5). These results provide new, specific insights into what types of interpretive themes players might typically use for these games. Some themes, such as players using textual information, are relatively straightforward. The themes also include novel findings, such as players relying on

prior gameplay experiences to interpret the play space in this new game, including basing interpretation of some STEM concepts in this game on similar concepts as modeled in other games. Other themes, such as players avoiding quantitative information, and assigning outsized meaning to visual phenomena also emerged. The results also show that formal representations of concepts through game assets and systems have an impact on how they are interpreted by players.

These results also showed that player mental models and understanding can shift through interacting and interpreting in-game models. However, the ability of the game to promote shifts in this knowledge is inconsistent. An unknown or misaligned model of a STEM concept was corrected only 57% of the time, 43% of the time players came away from the game without changed understanding.

These results also include five specific design recommendations supported by the data, specific to this game and this sample. Design recommendations stemming from player interpretive themes from this sample include 1. Developing ways to present quantitative information visually in the play space, 2. Carefully designing and testing visual style and rendering of graphic assets, 3. Designing improved feedback systems players must encounter, and provide feedback to highlight both inefficiencies and failures in game, 4. Integrating tutorials throughout gameplay, and 5. Providing a broader, linked information system and encyclopedia.

Finally, these results show the inconsistency and inadequacy of any single theory to predict or explain if and how learning occurs in games. There are notions of experiential learning loops, as well as articulated design principles that in some cases appear to be consistent with the results of this study, but the results show no single theory or framework for which the preponderance of the patterns and predictions appeared to be consistent with the findings. This suggests current theory in game-based learning is inadequate, and therefore there is a need for stronger theory, and perhaps a new direction for theory.

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Appendices

Appendix A: Recruitment Survey

University of Washington Games and Learning Study

This form is for youth interested in participating in the games and learning dissertation research- led by Travis Windleharth, of the University of Washington Gamer Group. Children capable of playing video games, and with access to a PC or MAC and in 6th, 7th, 8th, or 9th grade are eligible to participate. Children who have played the game Oxygen not Included are not eligible to participate.

The study consists of a short pre-activity survey, a 90 to 120 minute video game play session (which is recorded), and a separate post play survey. You may be invited for a second play session. All children that participate will receive a \$40 Visa gift card, and a copy of the STEM game Oxygen not Included.

If your child is interested, please fill out this short form with them or on their behalf, and our team will be in touch. If there are multiple interested children in your household, you may fill out the form multiple times. Thank you.

Questions.

1. How old is the interested child?

2. In what grade is the interested child?

3. What gender is the interested child?

4. What level of experience does the child have with video games?
 - A lot of experience
 - Some experience

Little to no experience

5. Would you (as caregiver) consent to gameplay video recordings of your child's play?
(Raw data are used only within the research team, and no identifying information is ever used for research participants).

6. What is your name?

7. What is your e-mail address?

8. What is the interested child's name?

Appendix B: Pre-Gameplay Interview

Hi, I'm going to ask you a few questions before we begin. Do I still have permission to record this interview and your gameplay? (Confirm)

What is your name, and what grade are you in?

What is your favorite subject in school?

What is your favorite game?

How much experience do you have playing video games?

Have you played strategy games before? (If so, what were they?)

What do you think a group of humans would need to survive inside of an asteroid in space?

What needs for these space colonists would need to be filled?

What kinds of things would help them survive?

What hazards do you think these space colonists would face?

What resources might they need to find?

(If respiration and atmosphere are not mentioned) What do you think these people would need in order to be able to breathe?

(If food is not mentioned) How might these people acquire food?

Appendix C: Instructions and Prompt List

While you play the game, you are going to engage in an activity called a “think aloud”, or think aloud interviewing. The entire time you play, I want you to keep talking about what you are thinking. Say whatever comes into your mind as you are thinking about what is taking place in the game, and say whatever you are thinking out loud as you are taking actions in the game.

There is no way to talk too much!

There are no “right” or “wrong” thoughts or actions, the most important thing is that you keep talking about what you are thinking about as many things as possible during gameplay. During this activity, I will also ask questions from time to time as well, about what you are doing, what you are thinking, and why.

Generic Think-Aloud Prompting

What are you thinking about?

What is happening?

What are you looking at right now?

Why were you hovering your mouse there?

What does that mean to you?

What were you thinking as you were hovering your mouse there?

What is your strategy here?

What are you trying to accomplish?

Observed Actions

What were you thinking when you (observed action)?

Why did you (observed action)?

Did you read any text just now? (What text did you read?)

How did you decide to do what you just did?

Interpretation

What do you think that means?

What does that mean to you?

How do you interpret that?

What do you interpret that to mean?

Why do you think that is happening?

Appendix D: Analysis Codebook

Code	Description
Textual Interpretation	A player using any sort of text (numbers, words, symbols) on screen to interpret something
Guiding Text	Reading and using tutorials and alerts that appear on the screen
Tooltips	Reading bits of information by clicking or hovering a mouse over game components
Data Tables	Reviewing a table of data available within the game
Visual Interpretation	Using visual assets to make sense of the game state
Iconography	Using signs (icons, indices, and symbols) to interpret phenomena in the game
Graphical Form	Making inferences from component image assets in the game
Weighting Visual Phenomena	Assigning great weight to a visual phenomenon in

	interpretation
Real World Models	Using an existing mental model (or schema) of the real world to interpret something in the game
Game Mediated Interpretation	Interpreting things in the game through the lens of other games
General Gameplay Patterns	Interpreting things in the game from other general gameplay patterns and mechanics
Model from Other Game	Interpreting things in the game based on similar characteristics in other, specific games
Game Mediated Real World Phenomena	Interpreting a real-world concept in a game, based on how it is modeled in another game
Proximal Problem Interpretation	Interpreting a problem or challenge as caused by a nearby but unrelated component
Quantitative Aversion	Conspicuously avoiding available quantitative information that is immediately useful
Aligned	Player mental model or belief aligns with the real world, as understood by domain experts
Differs	Player mental model or belief differs with the real world, as understood by domain experts
Unknown	A player expresses uncertainty or lack of knowledge about a specific concept

Table 11. Overview of codes.

Appendix E: Oxygen not Included Overview

Oxygen not Included is a science fiction simulation video game developed by Klei Inc., released in February 2017. It is known for its emphasis on STEM systems, and complex systems thinking required to succeed at the game. The premise of the game is that the player controls a small colony of space travelers who somehow find themselves mistakenly transported deep below the surface of a resource rich asteroid, and must survive while trying to find their way out. This requires that the player carefully collect and manage resources, and design solutions to provide life support and hazard mitigation for the characters (also called, duplicants, or “dupes”). The game models numerous physical, chemical, electrical, thermal, and fluid dynamics that affect the behavior of the game world, and players must understand and manage the impact of these behaviors to succeed.

The core systems that are modeled in the game can be more closely examined with “overlays” that players can use to collect information about the environment and the game state. These overlays are limited to providing some basic information about the attributes and characteristics of component blocks in the game. The key systems in the game include atmosphere, power, temperature, materials, light, ventilation, plumbing, germs, farming, decor (aesthetics), and automation. The systems are interconnected and can affect one another, based to a significant degree on how these systems behave in the real world.

Atmosphere

The atmosphere overlay shows the breathability of gasses in the environment, in terms of supporting life. While the overlay indicates where oxygen is present in significant enough amounts to breathe in blue and light blue colors, the overlay does not indicate why there is no

breathable atmosphere in an area, which could be due to simple lack of oxygen, toxic gas, low pressure, or vacuum.



Figure 8. Atmosphere Overlay

Gasses in the atmosphere are modeled to behave as they do in the real world, with heavier gasses like carbon dioxide tending to sink, lighter gasses like helium and natural gas tending to rise, and gasses will tend to flow from areas of higher pressure to areas of lower pressure. Different components can emit or transform into gasses. Some examples include humans inhaling oxygen and emitting carbon dioxide, plants taking up carbon dioxide and emitting oxygen, water entering the atmosphere as steam when it reaches its boiling point, and hydrogen and oxygen entering the atmosphere from catalyzed water.

Key atmospheric challenges players must grapple with are generating enough oxygen to survive, managing toxic and germ filled gasses, and managing atmospheric pressure.

Temperature

Heat and temperature are modeled with a high degree of complexity in the game and must be monitored and managed by the player. The materials and components in the game all have different thermal properties, such as capacities, conductivities, and melting points. Some

components such as generators and machinery give off heat when operated, and some chemical reactions such as composting and catalysis also introduce heat in the environment. The temperature overlay (fig x.) shows the temperatures and thermal tolerances of components in the game environment.



Figure 9. Temperature Overlay

Heat must be managed to maintain a safe and comfortable temperature for characters, or the player may experience hypothermia or heat stroke. Extreme temperatures will harm and kill characters. Players can manage heat using a wide range of engineered solutions such as creating insulation, using ventilation, fluid circulation, and creating heat sinks. Players can also construct objects using a range of materials, to take advantage of different thermal characteristics. Given the closed nature of the game environment, heat management becomes more difficult as the game progresses.

Power

Oxygen not Included models electrical power, which includes building sources of generation, transmission, load management, and storage.



Figure 10. Power Grid

Long term survival in the game requires that players find a way to generate, distribute, and store power, as power is required to operate most types of machinery, including life support machinery. Players need to develop power generation, create capacity for power storage, and manage transmission, including load control using transformers.

Ventilation

Ventilation systems can be designed to manage gasses in this game, and the atmosphere and ventilation systems are intimately connected. Players can build air pumps, air filters, ducting, and vent systems, as well as methods of gas storage.

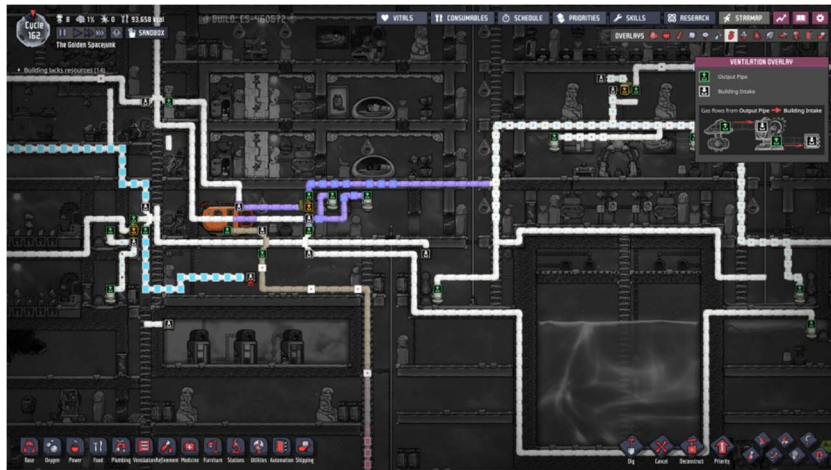


Figure 11. Ventilation Overlay

The most significant goal of ventilation is to ensure plenty of clean oxygen in the characters' base and areas of operation, and remove polluted or poisonous air. However players can also engineer ventilation solutions to clean air, manage air pressure, and collect, store and distribute gasses useful to other systems, such as chlorine, hydrogen, and natural gas.

Plumbing

Plumbing, and more fundamentally liquids management, are modeled in detail in Oxygen Not Included. Players find reservoirs of both clean and polluted water in their environment, and will need to devise water storage, filtration, and transportation solutions, as well as manage sewage and wastewater treatment. The plumbing overlay shows systems of pumping, piping, filtration, and storage of various liquids in the game. Water is the primary liquid of concern as it is central to survival, but other liquids such as coolant, oil, and petroleum can be handled as well.

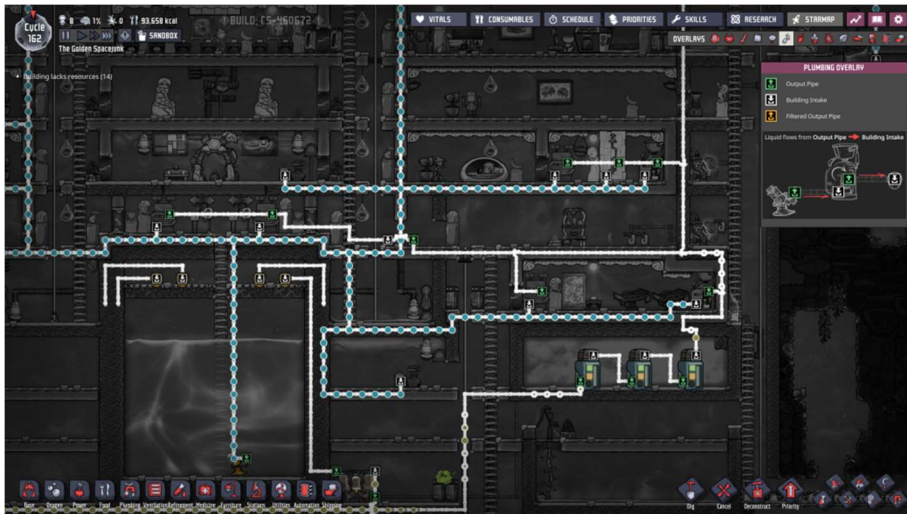


Figure 12. Plumbing Overlay

Challenges players will face with regard to liquids and plumbing are finding sources of water, managing sewage, building filtration and sterilization systems, and managing piping (including keeping them from freezing and breaking, or overheating and exploding). Since water has a high heat capacity, it tends to impact temperature management, and pumping systems are dependent on power.

Germ Overlay

The germ overlay shows type and amount of microbes in the atmosphere, in fluids, as well as on surfaces in the game. This includes microbes tied to food poisoning, allergies, and respiratory disease. Characters can manage microbes through various tasks and technologies such as manual cleaning and disinfection, ventilation and filtration, and chlorination.



Figure 13. Germ Overlay

Farming Overlay

The farming overlay maps out plants in the environment that can be harvested for food and resources. This includes wild plants as well as plants cultivated in soil, planters, and hydroponic greenhouses. During the course of the game players can find seeds that can be planted, as well as develop technologies for growing food and increasing food production through composting, fertilization, and micronutrients.



Figure 14. Farm Overlay

Materials, Light, Automation, Decor

Materials, light, decor, and automation are four additional overlays available to players. These overlays are somewhat simple, and focus on narrow aspects of the game environment. The materials overlay reveals what types of materials are near the player. The light overlay shows various levels of illumination in the game space. Automation is a late-game technology that allows players to build “smart” systems connected by logic gates. And decor is an overlay that maps the aesthetic pleasantness of the environment using an abstract point system. Decor impacts character morale and productivity, and is decreased by machinery, detritus, exposed piping and wires, and decor is increased by decorations, art, architecture, and plants.