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# Interdisciplinary Design of Game-based Learning Platforms

## A Phenomenological Examination of the Integrative Design of Game, Learning, and Assessment

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# Contents


1 **Introduction and Prior Research Review** . . . . . . . . . . 1

2 **Chronicle of Designing a Game-Based Learning Platform** . . . . . . . . . 15

3 **Interdisciplinary Design Activities and Patterns** . . . . . . . . . . 51

4 **Design of Gameplay for Learning** . . . . . . . . . . 77

5 **Interweaving Task Design and In-Game Measurement** . . . . . . . . . . 101

6 **Designing Dynamic Support for Game-Based Learning** . . . . . . . . . . 121

7 **An Evolving Design Framework for Game-Based Learning Platforms** . . . . . . . . . . 143

**Index** . . . . . . . . . . 155

# Chapter 1
# Introduction and Prior Research Review

**Abstract** Games are not just a vehicle to enhance learning but a new way of understanding and organizing learning. The starting point of an optimal integration of learning and play in the game setting is to identify the salient elements of learning itself and the inherent learning processes in gameplay. In this introductory chapter, we discuss relevant theoretical perspectives on the nature of knowledge and learning that guide the exploration of playful elements in learning and consequently the opportunities for learning that games offer. We then provide a conceptual review of prior research of game design and discuss the challenges and the interdisciplinary nature of educational game development. In the end, we introduce the overall goal, structure, and chapters of this book.



## 1.1 Games for Learning

AU1 The best way to motivate students to embrace learning is to "make it fun", and hence making learning fun seems the most well-known claim on the educational power of games (Kim, Song, Lockee, & Burton, 2018). Games are structured or organized play, requiring the player to follow a specific set of rules to tackle obstacles and attain a goal (Klopfer, Osterweil, & Salen, 2009; Suits, 1978). Although games are typically considered as a high-quality multisensory rendering environment, the main reasons for the interest in game for learning are not the medium's success but the motivation of players and their deep engagement while playing (Denis & Jouvelot, 2005).

While learning and play are often associated with opposite connotations (Mitgutsch, 2009), learning and play share a key attribute: Both are challenging, long, and interactive processes that require cognitive effort and willingness to acquire new knowledge or skills. Yet people tend to avoid and dislike challenging learning experiences in the educational setting while engaging in and enjoy gameplay as a form of *hard fun*. This observation, along with the interest in creating intrinsically motivating learning, has triggered the examination of games as a promising tool and environment for learning. Particularly, prior research has



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focused on defining the nature and circumstances of “pleasantly frustrating” learning experiences and how these are and can be aligned with the gaming experience (e.g., Gee, 2003; Rieber, 1996). Some scholars have also examined the phenomena of game engagement from both intrinsic motivation and well-internalized extrinsic motivation perspectives (e.g., Csikszentmihalyi, 1997; Deci & Ryan, 1985; Malone & Lepper, 1987).

The idea of using games for learning purposes was discussed early by Clark C. Abt in 1975 and further formulated by other scholars of serious games (e.g., Breuer & Bente, 2010; Charsky, 2010; Sawyer, 2003; Susi, Johannesson, & Backlund, 2007). The educational purpose can be assigned to a game in the design, or by the context it is used. Games designed primarily for entertainment, like commercial off-the-shelf (COTS) games, can be used in a teaching and learning context, though its learning effect is an exogenous one.

Despite the innate connection between gameplay and learning, not all forms of games are equally suitable for learning purposes; simply adding educational material to an enjoyable game or presenting it in a game-like setting will not create an engaging and effective game for learning purposes (Breuer & Bente, 2010; Ke, 2016). A frequent cause of a segmentation between play and learning in a game is that win criteria for a game do not necessarily equate with the things players are supposed to learn through playing the game (Van Staalduinen & de Freitas, 2011). Specifically, there are variant categories of learning in games, including things that we can learn and are deliberately designed in a game (or intentional learning), things that we can learn but not necessarily designed into the game (or collateral learning), and things that we must learn in a game to successfully finish the game (Becker, 2008). The desirable situation is that the first two categories overlap with the third one, in that both intended and incidental learning are enabled and assured by gameplay. The starting point of an optimal integration of play and learning in the game setting should be to identify the potential enjoyment (or the playful elements) of learning itself and the inherent learning processes in gameplay (Rodriguez, 2006). Hence, games are not just a vehicle to enhance learning but “a new way of understanding and organizing learning” (Breuer & Bente, 2010, p. 14). AU2

In this introductory chapter, we describe relevant theoretical perspectives on the nature of knowledge and learning that help us to explore playful elements in learning and consequently the opportunities for learning that games offer. We then provide a review of prior research of game design and discuss the challenges and the interdisciplinary nature of educational game development. We introduce the overall goal, structure, and chapters of this book at the end.

## 1.2 Nature of Knowledge and Learning Pertinent to Games

Dewey defined knowledge as “not information, but a mode of intelligent practice and habitual disposition of mind” (p. 124, 1910). This definition highlights two salient elements of knowledge that are apt to frame the design of game-based learning: a practice that crafts and enacts intelligence and intelligent habits or ways of thinking constituted in the practice. The intelligent practice, called reflective inquiry by Dewey, comprises mainly the processes of identifying a problem (i.e., a quandary that needs to be resolved), studying the problem through active engagement, and reaching cognitive conclusions as the problem is resolved. The central facet is the *method* by which a cognitive conclusion is reached; hence, the process/action of identifying, actively studying, and resolving a problem, more than the cognitive conclusion itself, is the item of value (Dewey, 1929; Hiebert et al., 1996). During the action of inquiry or problem-solving, *scientific attitude*—"willingness to endure a condition of mental unrest and disturbance" or that is capable of enjoying the doubtful—should be deliberately constructed and is alone worthy of the title of knowledge (Dewey, 1910, p. 13). In view of that, perfecting the method of inquiry and constructing scientific attitude are more significant to realize the meaning of knowledge than that of acquiring and utilizing information and technical procedures.

Derived from Dewey's perspective is the argument for *problematizing* subject matter knowledge (Hiebert et al., 1996). "Allowing the subject to be problematic means allowing students to wonder why things are, to inquire, to search for solutions, and to resolve incongruities" (Hiebert et al., 1996, p. 12). The conventional conception of problem-solving typically focuses on the *application of acquired knowledge* in realistic situations, whereas problematizing a topic emphasizes *knowledge acquisition*. Problematizing mathematics, for example, involves treating experiences as problems, examining or manipulating them via *overt doing*, and consequently constructing *structural understanding* that includes insights into the structure of mathematical objects, strategies for solving problems (both procedures used for particular problems and general ways of thought needed to construct the procedures), and dispositions toward mathematics (e.g., seeing mathematics as an intellectual activity in which they can participate). Notably, real-life problems provide a legitimate context for problematizing mathematics, though it is only one context for it. The value of a real-life problem depends on whether students problematize the situation and whether it offers the chance for students to acquire structural understanding after problem-solving. In other words, the knowledge to be acquired depends as much on the mathematical ideas embedded in the task (e.g., a game-based inquiry) as on the way it is packaged. Therefore, the focus of the design research of learning in games is not only on what subject content or information is integrated but *how core game tasks will legitimize subject-problematizing actions to generate structural understanding*.

In alignment with the aforementioned learning perspectives is the proposition to establish the learning activity or task as an *epistemic practice* (Eriksson & Lindberg, 2016). With a similar assumption that knowledge is constituted in people's actions, an epistemic learning practice is characterized by open and question-generating objects (or tasks) that the learners work with. Apart from contextualizing a learning task in relation to students' everyday interests, it is important to choose and shape a task so that the students discern that the previous tools and solutions they are familiar with are restricted. When working with the learning task, students get to test previously developed methods and tools and (re)develop theoretical generalizations that are characteristic for a specific subject. In other words, the learning task should be developed to enhance such kinds of theoretical thinking, by requiring that “core principles” or “conceptual relations” constituting a specific knowing are discerned and understood through learning actions in a content-rich epistemic practice.

In summary, the above theoretical underpinnings for learning in games suggest that the acquisition of discipline-specific, structural understanding (or theoretical thinking), compared with the application or acquisition of static content or information, is more crucial for the goal of the learning-play integration. Subsequently, designing gameplay as an epistemic learning practice that delineates subject-problematizing actions is a fundamental means to establishing game-based learning. Educational game design is to create meaningful, interactive, and challenging experiences involving the user as the conductor of his own intellectual practice and development.

## 1.3 Designing Games for Learning

### *1.3.1 Research of Game Design*

The content of a game is its behavior, not the media that streams out of it toward the player (Hunicke, LeBlanc, & Zubek, 2004). The difference between games and other design artifacts is that their consumption (by players) is relatively unpredictable, because the interaction between players and the coded game subsystems creates dynamic and often unpredictable behaviors (Hunicke et al., 2004). Gameplay is hence defined as the structures of player interaction with the game system and interaction with other players (Bjork & Holopainen, 2004).

Although game design is a frequent theme of textbooks and articles, a unified design theory diagnosing and predicting the structural relations between desirable gameplay and game subsystems is still lacking. The *mechanics, dynamics, and aesthetics* (MDA) framework by Hunicke et al. (2004) is an earlier effort contributed to this aim and is described as the three sectors of a game system. Mechanics are various actions, behaviors, and control mechanisms afforded to the player within a game context. Dynamics refers to the run-time behavior of the mechanics acting on player inputs over time or gameplay. Aesthetic represents the desirable emotional responses or experiences evoked in the player. From the designer’s perspective, the mechanics give rise to dynamic system behavior, which in turn leads to particular aesthetic experiences. From the player’s perspective, their respective player or aesthetic experiences, such as sensation, fantasy, challenge, fellowship, discovery, and expression, are brought forth by observable dynamics and, eventually, operable mechanics. Even though the MDA framework lacks instruction detailing the combination and proportion of mechanics that will result in variant aesthetic goals, it helps to describe how and why different games appeal to different players or to the same players at different times. It should be noted that in games for learning purposes, the desirable player experiences are not just emotional responses but more cognitive involvement. However, inadequate game design research addresses the mechanics and dynamics in relation to the cognitive facet of player experience.

Extending the MDA framework, Salen and Zimmerman (2005) discussed *meaningful play* as an emotional and psychological experience in a game that emerges from the relationship between player action and system outcome. Specifically, they described that meaningful play occurs when the relationships between gaming actions and their outcomes in a game are both *discernable* and *integrated* into the larger context of the game. Discernable means that the result of the game action is communicated to the player in a perceivable way. Integrated means that an action a player takes not only has immediate significance in the game but also affects the play experience at a later point in the game. In other words, game design is the process by which a designer creates an interactive and engaging system to be encountered and proactively investigated by a player, from which meaning emerges. Importantly, interactivity afforded by the coded/designed system comprises not only *functional interactivity* (or the usability of the interaction interface) but also *cognitive interactivity*—psychological, emotional, and intellectual participation between a participant and a system.

Prior research of game design tends to depict play experience as the product of coding operable mechanics and observable interactivity. But there is still a debate between ludology and narratology in the game design literature. In comparison with the argument for ludology—systems of puzzles, rules, and interactivity designed to frame play or fun (e.g., Adams & Dormans, 2012; Koster, 2013; Salen, Tekinbaş, & Zimmerman, 2004)—the narratology proposition (e.g., Jenkins, 2004) emphasizes the design of narrative structure as the anchor of play experience, describes the importance of designing *environmental storytelling* via spaces and artifacts in a game, and argues that gameplay enacts a personally meaningful story or life experience whether story is a defining game feature or not.

Recent discussions of game design (e.g., Adams, 2014; Schell, 2014) manage to coordinate the perspectives of ludology and narratology by arguing that mechanics (or interactivity) and environmental storytelling (or embedded narrative) in a game, jointly and ultimately, serve the purpose of *experience design*. Play or fun is co-framed by players' prior experiences, the designed game system, and the emergent interactivity (dynamics) between the players and the system. Even though components of the experience to be designed are well specified in the game literature, the paths toward the goal are dynamic and murky. Due to such a dynamic and participatory nature of play experience design, mostly game design is based on the intuition and experience of designers with the infield experimentation and iterative refining. Descriptive or analytical analyses of the game elements, design rationales, and experimented design strategies, however, will help to guide the experimentation. Particularly, empirical and longitudinal research on variant processes of design creation and experimentation in diverse game design projects will help us construct the collective knowledge as well as a unified while scalable theory of game design.

### *1.3.2 Prior Research of Educational Game Design*

Multiple conceptual or design models of educational games, or game-based learning platforms, have been proposed in the literature of instructional design and learning technologies. For example, Kiili (2005) proposed an experiential gaming model that reflects the perspective that learning is a construction of cognitive structures through action or practice in the game world. The model depicts game challenges (or problems) as the center of game-based learning flow by initiating active experimentation, reflective observation, and schemata construction. Kiili's model outlines the process of experiential game-based learning with its implications for educational game development but lacks a design description of the game systems. Amory (2007) described a theoretical framework, called the game object model, for educational game research and development. The model sets game space, problem space, and social space as the three components of the educational game system and prescribes a list of defining features for each space. For example, drama, role models, interaction, and gestures are listed as the game space features; explicit knowledge, literacy, and information communication are considered design elements of the problem space, while the social space includes computer-mediated communication along with social network analysis. In general, Amory's game object model presents a visionary integration of related theoretical constructs of gaming, learning, and social community. It has not explained the actual design mechanism and lacked technical definitions of the theoretical constructs for designers. Similarly, de Freitas and Oliver (2006) used a four-dimensional framework to summarize the key analytical or evaluation constructs (i.e., learner specifics, pedagogy, representation, and context) of a virtual-world and gaming-based learning environment. These aforementioned generic models are all aimed to outline and categorize related constructs underlying the integration of gaming and learning processes. They focus on a conjectural or an interpretive analysis of the relationships and structure of these constructs as a system, from more of an educational researcher perspective. Other works, such as that of Calvillo-Gámez, Cairns, and Cox (2015) and Dickey (2007), intend to explore educational game design from the player or user perspective. They highlight an interpretive and evaluative analysis of the salient elements with corresponding design norms of an optimal gaming experience and then discuss how such design norms can be extended with or transferred to the instructional design principles.

Empirical studies examining educational game design approaches and features, compared with those evaluating a game's learning effectiveness, are limited. Our recent review of the literature with the searching phrase of "game design" + "learning" or "education" generated mostly articles that examined game design as a learning-by-making activity by participants (e.g., Kafai, 2012; Robertson & Howells, 2008) or used game design elements in nongame educational settings (e.g., Deterding, Dixon, Khaled, & Nacke, 2011). Published design research of educational games is frequently a conjectural or an evaluative analysis with existing COTS or serious games (e.g., Annetta, 2010; Dickey, 2007; Mitgutsch & Alvarado, 2012). Pinelle, Wong, and Stach (2008), for example, discerned 10 principles of game usability—"the degree to which a player is able to learn, control, and understand a game"—after reviewing 108 different games from 6 major game genres (p. 1453). These usability principles, applicable for game design in general, are allowing users to customize video/audio settings, difficulty, and game speed, allowing users to skip non-playable and frequently repeated content, and providing (a) unobstructed views appropriate for the user's current actions; (b) intuitive and customizable input mappings; (c) controls that are easy to manage and that have an appropriate level of sensitivity and responsiveness; (d) users with information on game status, providing training and help; and (e) visual representations that are easy to interpret and that minimize the need for micromanagement. All these game usability principles are transferrable to the design practice of educational games and are highly consistent with the infield experimentation findings of our current project.

On the other hand, there is still a lack of studies, especially design-based ones, that present infield testing or design experimentation findings governing the development processes and strategies of educational or serious games (Torbeyns, Lehtinen, & Elen, 2015; Warren & Jones, 2017). In particular, a rich, data-driven, and theory-contributing description of educational game design exploration and findings should help us develop structural and in situ knowledge of game design. The studies by Andersen, Butler, O'Rourke, Popović and their colleagues (2011, 2014, 2015), for example, examined variant design features and development mechanisms, from game objective, level progression strategy, and incentive structure to scaffolding, of a math learning game (called "refraction"). Based on the play data of online gamers and the perspectives of human computer interaction and educational psychology, their research efforts and findings helped to illustrate diverse design challenges, the framework of design solution exploration and generation, and solution validation/refining strategies during the educational game design process. In another example, Denis and Jouvelot (2005) conducted a case study on design strategies that were aimed to reconcile learning and fun in a video game dedicated to music education. Building on the self-determination motivation theory (Deci & Ryan, 1985), they explored game design patterns or features that helped to reinforce competence, autonomy, and relatedness in game-based learning. Their design-based research contributed tangible heuristics of educational game mechanics design, including reifying values into rules to convey knowledge in interactions rather than static data, providing the player expressive ways to confront with and test rules, tuning usability so that entry barriers (e.g., technical difficulty or the game's gender bias) that go against the player's urge to practice gameplay will be leveled, sequential embedding of novel challenges and information in game levels to present a positive slope of the learning curve, and a natural and stealth assessment mechanism of in-game performance. All of these previous learning integration game design suggestions have shed light on our design efforts in this current project and were later corroborated by our project findings.

### 1.3.3 *Enduring Challenges and Interdisciplinary Nature of Game-Based Learning Design*

The design of games for learning resembles the innate challenge of entertainment game design: a definite formulation of gaming behaviors or consequences is difficult because interactions between players and the coded game system are often complex, dynamic, and unpredictable. Moreover, play is voluntary and intrinsically motivating and involves proactive cognitive engagement that allows for the freedom of effort and interpretation, whereas these characteristics do not automatically apply to game-based learning (Shute & Ke, 2012). Therefore, existing approaches and tools for developing entertainment games cannot simply be transferred to educational games or game-based learning platforms. There are multiple enduring and distinctive challenges associated with the design of games for learning.

First, problematizing a subject and reinforcing an investigative or epistemic practice with problem-solving are believed to be crucial to game-based learning, as discussed above. But not all domain knowledge or topics share the same approach or advantage in being problematized. Certain learning processes are by nature abstract and sign-mediated and hence cannot always be situated or contextualized. Reality isn't always "fun"—mechanics that impact the dynamics to create the desirable emotional responses may negatively impact the game's ability to recreate the reality of epistemic practices to be simulated. In particular, we lack understanding of how to design a game to reinforce purposeful development of abstract or symbolic domain knowledge.

Second, a game is typically an open-ended learning environment that emphasizes self-regulated experiential learning as well as reflective inquiry. However, not all students are by default self-regulated learners or capable of performing sense-making during game-based problem-solving. Students also differ in their prior domain knowledge, game skills, motives for gaming, and preferences in relation to modes of play. Their attention span with textual information in the game world can be vastly reduced due to the multisensory rendering environment. Given such a heterogeneous player group and the goal to engage and educate all students with a single game-based learning platform, designing a motivating while learning-constructive gaming experience is particularly challenging.

Third, prior research and practice of game-based learning tends to underline a stealth (or incidental) learning idea. Such a perspective is sensible especially when only generic scientific attitudes and generic thinking skills are the focus of learning outcomes. On the other hand, learning by nature is a conscious activity. The desirable player responses in game-based learning should not be just emotional but cognitive, metacognitive, and domain-specific. Inclusion of the idea of informed and intentional learning in games (Annetta, 2010) will entail the integration of gameplay-coherent learning supports in the game that promote purposeful knowledge construction while maintaining motivation and the game flow. A general game design framework (e.g., the MDA framework) has to be extended to address these additional facets of aesthetics or player experience. Corresponding with the inclusion of intentional learning to game-based learning platform design is the challenge to build and coordinate functional usability/interactivity and cognitive usability/interactivity. Rather than creating an intuitive interface, one should also design the interface to be intermediary between gaming actions and action-based knowledge construction.

Ultimately, another unique change of educational game design is to develop embedded assessment for game-based learning outcomes that assess performance-based competency development. Even though recently there is increasing research on the methods of educational data mining in game-based learning assessment, designing and using games as both a learning and an assessment tool are challenging in that gradual learning progression can be in conflict with evidence accumulation for assessment in the game setting. How to achieve an integral design and development of learning tasks and the tasks that discern competency status remains murky.

**Interdisciplinary Nature of Game Design** Games, acting as an interactive microworld, a digital toy, and an environmental storytelling device simultaneously, call for the integration of multiple disciplinary perspectives and approaches. A game artifact involves the application of communication/information design, visual design, human-computer interaction, and software engineering. Designing games as an effective learning platform, given all of the abovementioned challenges, entails interdisciplinary knowledge and methods of additional disciplines, such as the subject domain knowledge, learning system design, psychology, and educational measurement. Interdisciplinary collaboration among the design team members from these different fields, by itself, is a challenging process. It has to balance and incorporate their often conflicting values, ways of thinking, domain-specific language, and methods, especially those of game designers, instructional designers, content experts, and psychometricians. Although cross-cultural communication and interdisciplinary design are recurrent topics in workplace studies and engineering education research, the functional processes and patterns of interdisciplinary design for game development are generally absent in the literature.

## 1.4 Goal and Structure of the Current Book



In spite of the plethora of research on game-based learning, the design descriptions or operational conjectures on how to effectively and intrinsically design intentional, domain-specific learning in gameplay are scarce. Multiple enduring challenges associated with educational game design remain unaddressed. The previous efforts to explain the framework of game-based learning typically focus on an evaluative analysis of existing games or present a general and theoretical level of reasoning, thus lacking tangible guidance for the actual educational game design. Game design is multidisciplinary in nature, yet few efforts have contributed to describing the interdisciplinary design process, techno-pedagogical design knowledge, or accessible design language.

Based on the 4-year design and research of an architecture simulation game for mathematical learning (called E-Rebuild), this book is aimed to present a phenomenological examination and explanation of a functional design framework for games in education. It aims to provide a rich description of the experiences and perceptions of designing a digital learning game and of performing interdisciplinary collaborative design among experts of different fields.

Specifically, it will address both practical and conceptual issues about the design of play-based learning systems that aligns and interweaves game and learning mechanics, evidence-centered design of learning tasks and assessment, and in-game learning support. It also aims to explicate the process of coordinating the interdisciplinary language and perspective differences in design communication and negotiation for the future development of learning games.

In Chap. 2, we provide an overview of the integrative, interdisciplinary design process of E-Rebuild and the adopted phenomenological research approach. Core phases of designing a game-based learning platform are illustrated with a longitudinal log of the iterative design, experimentation, and refining of E-Rebuild. In Chap. 2 we also present a positioning statement and design reflection notes of each co-author (and interdisciplinary design team member). In Chap. 3, we explain salient interdisciplinary design activities and patterns that emerged from the E-Rebuild project. The description of the interdisciplinary design patterns in this chapter consists of a contextualized design narrative/account of core design processes and an analytical synthesis of core design pattern elements—a *design problem statement* with its context and specifics, the *solution* or technique (with its key structure or mechanism) to solving the stated problem, and the *pattern* of transferring or scaling this design solution or design move. In Chap. 4, we report design challenges associated with the core components of gameplay and review the gameplay design propositions and infield test findings of E-Rebuild. We discuss how domain-specific learning is integrated in and activated by core game actions, rules, game objects, and the game world design. In Chap. 5, we describe an integrative-design approach that interweaves game-based task design with in-game assessment of learning. We discuss core design processes and functional conjectures on the approaches of task generation and evidence accumulation, with support of infield observations on the implementation feasibility and outcomes of the design assumptions. In Chap. 6, we explore the design of dynamic game-based learning support. We review prevalent practices and prior research of scaffolding and support in game-based learning, share our observations of the obstacles that learners experienced in game-based learning processes, and report the corresponding learning support strategies with infield testing findings of E-Rebuild. In the conclusive Chap. 7, we discuss an emerged, functional design framework for game-based learning platforms, with a summary of the design problem structuring process for the interdisciplinary, integrative design of game-based learning. We conclude the chapter and the book by discussing potential directions of future design and research efforts of game-based learning design, with a set of core design concepts highlighted.

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# Chapter 2
# Chronicle of Designing a Game-Based Learning Platform

**Abstract** Our phenomenological examination of learning game design is situated in a 4-year, longitudinal design-based research project that encompasses iterative design processes to develop, refine, and study a game-based learning platform called E-Rebuild. This chapter presents an introductory overview of the four facets of the interdisciplinary educational game design—interdisciplinary collaboration, learning-play integration, integrative task and assessment design, and game-based learning support. We then provide a design chronicle of E-Rebuild as the key setting of the phenomenon examined, by explaining its iterative design, testing, and refining processes. The authors' researcher positionality and reflective summaries of design experiences are presented as well.

## 2.1 Introduction

Adopting a phenomenological perspective, we aim to *describe* as rich and accurately as possible the phenomenon of designing a game for the learning purpose (or a game-based learning platform), from the perspectives of people involved while refraining from pre-given frameworks (Giorgi, 2009; Groenewald, 2004). The examination evolves around two overarching questions: *What is it like to design a game for the learning purpose? What salient design patterns, strategies, and understandings have been derived from the design effort?*

Our phenomenological examination is situated in a 4-year, longitudinal design-based research project that encompasses iterative design processes to develop, refine, and study the game-based learning platform in situ. Specifically, we have been designing and developing an architecture simulation game-based mathematics learning platform (called *Earthquake Rebuild* or *E-Rebuild*) that also incorporates evidence-centered learning assessment via an unobtrusive collection and analysis of performance data. A major conjecture of E-Rebuild is that architectural design and modeling via this simulation game-based learning platform will engage middle-school students in problem-centered learning and epistemic practice of mathematics.





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Informants or participants are nine members of the design team of E-Rebuild. They include the four authors of this book, in addition to one learning scientist, two game programmers who are graduate students who majored (or are majoring) in scientific computing and computer science, one student instructional designer, and one architect consultant. We have examined the data derived from archived design and meeting notes, open-ended interviews, observation notes, and an artifact analysis with the game that was iteratively designed and refined during the 3 project years.

We analyzed the qualitative data in an attempt to identify themes and make functional generalizations regarding the nature and perceived experience of collaboratively designing a game-based learning platform by an interdisciplinary team. Following a general framework of phenomenological inquiry (Giorgi, 2009; Groenewald, 2004), we have bracketed our positionality (as described in a later section), delineated and clustered units of meaning from the data to form the themes, and then extracted general and unique themes to make a composite description of every facet of the phenomenon. These thematic descriptions of the interdisciplinary game design are presented in Chaps. 3, 4, 5, and 6.

In this chapter, we present an introductory overview of the four facets of the interdisciplinary educational game design that will be discussed in details in later chapters. We then provide a design chronicle of E-Rebuild as the key setting of the phenomenon examined, by explaining its iterative design, testing, and refining processes. Ultimately, the authors' researcher positionality and reflective summaries of design experiences are presented.

## 2.2 Core Facets of Interdisciplinary Educational Game Design

Four core facets of game design, governing the heuristics of interdisciplinary collaboration, learning-play integration, integrative task and assessment design, and game-based learning support, have emerged from the thematic analysis of qualitative data. The first facet depicts general patterns framing the allocation and negotiation of collaborative design efforts during every phase of game design. The second facet sets the tone for the rest of game design with a specification of core gameplay —what, in which way, and when learning is legitimized by basic game actions, rules, and settings. The third facet involves a systematic development of game tasks that exemplify and assemble core actions in meaningful contexts, to not only enable subject-specific learning progressions but also discern and accumulate performance evidence of competency development. The fourth facet captures the design endeavors to reinforce players' motivated and intentional cognitive efforts contributed to game action-based knowledge application and acquisition.

### *2.2.1 Managing Interdisciplinary Collaborative Design*

The challenges of collaborative design by an interdisciplinary team relate to the management of unshared languages, values, and habitual methods ascribed to different forms of design, technological, and educational endeavor, within which is a mutual lack of awareness of each other's theoretical stance and motives about game-based learning. As Weingart (2000) identified, the way in which we see the world and approach novel problems is affected by a host of subcultures that are specific to individual disciplines, making truly interdisciplinary working difficult to achieve. The disciplines of education, mathematics, architecture, and scientific computing, in this case, have their own theoretical or applied stance toward education or design, criteria for appraising quality (e.g., of an effective learning experience or a design artifact), and their own ways of working (e.g., with design and teamwork).

For example, in spite of a general consensus among the interdisciplinary design team on the importance of engaging students in authentic and constructive learning, we differed in our original understanding of the underlying design constructs, such as the definition of a game, the nature of mathematics, the dynamics between learning and play (or fun), and interdisciplinary subject matters (e.g., mathematics in architecture). These different theoretical stances are exacerbated by our differences in epistemic frames (e.g., being designer, programmer, educator, or evaluator), experience of gaming technologies as both a consumer and a developer, understanding of the target users (e.g., middle-school students and the school setting), as well as our prioritized motives (e.g., research of game design or learning assessment, mathematics education, or design education). All these differences are reflected in language, design ideas or concepts, and preferred representation of concepts.

Given such a heterogeneity, the interdisciplinary collaborative design is never a simply division of work or a sum of ideas or expertise. Instead, there is an intentional and ongoing effort contributed to building a common design culture among the interdisciplinary team, including the specification of common concepts and language, the explanation and selection of the theoretical and design conjectures underlying the aforementioned design constructs, and the negotiation of an overarching design goal with a tangible design agenda that reflects the dynamics of different epistemic perspectives on learning, game, assessment, and the embedded subject matters. Last but not least, the team has explored and gradually established an informal protocol or routine for collaborative working and decision-making. This protocol deals with the balance between collaborative brainstorming and efficient decision-making, the integration of self-governing obligations and overlapped responsibilities, and the approach of information sharing and archiving.

### *2.2.2 Designing Gameplay for Learning*

Integrating the design perspective about an optimal integration of play and learning in gaming (e.g., Breuer & Bente, 2010; Rodriguez, 2006) and the argument for constituting knowledge in actions (Dewey, 1929; Hiebert et al., 1996), coding game mechanics (or interactivity) evolves around the effort of understanding and organizing mathematics as inquiries or subject-problematizing practices. As the data illustrated, the exploration of core gameplay involves two dimensions: (a) specifying a series of game *actions* that embody mathematical learning as an intellectual inquiry or practice and (b) designing coherent game objectives, obstacles (constraints), and rewarding rules that legitimize an active performance of these actions by the players, thus creating the desirable, learning-constructive interactivity between the players and the game system.

Along with the core game action and rule set are the interactivity interface (or the player input/output controls) and the game settings (or environmental storytelling) that should work coherently to foster and motivate emergent functional and cognitive interactivity between the players and the game system. In a game-based learning platform, a user interface should not only promote an "intuitive" action but also intermediary, discipline-specific theoretical thinking during the action. Designing game settings (or a game world) for the learning purpose is more than environmental storytelling. Game objects and scenarios in E-Rebuild, for example, embody the external representation of game-based, interactive mathematical problems for the players to investigate and solve. Therefore, designing gameplay for learning is to design a series of subject-problematizing actions that are structured by a set of rules and obstacle-tackling objectives, an intermediary action interface, and a coherent game world as both the milieu and drive of the actions.



### *2.2.3 Integrative Design of Game-Based Learning Task and Assessment*

A fundamental theoretical stance toward the nature of game-based learning (Eriksson & Lindberg, 2016; Hiebert et al., 1996), as discussed in Chap. 1, is that the knowledge to be acquired depends as much on the mathematical ideas embedded in the task as on the way it is packaged. Therefore, the focus of the design is not only on what subject content or information is integrated but *how core game tasks will exemplify subject-problematizing actions to generate understanding*. In other words, the game-based learning task should be developed to enhance sign-mediated, subject-related theoretical thinking (Eriksson & Lindberg, 2016), by requiring that "core principles" or "conceptual relations" constituting a specific knowing are discerned and understood through learning actions in a game-based task.

Apart from designing inquiry- and understanding-generating tasks, another core design challenge related to intentional learning in gaming is stealth assessment that enables the real-time capture and analysis of performance-based competency development data. With the recent methodology development in educational data mining and learning analytics, stealth learning assessment based on the dynamic performance of players could better capture process and performance-oriented evidence on competency development while not being intrusive to distract players' gameplay or state of flow.

Using the evidence-centered design approach (Almond, Mislevy, Steinberg, Yan, & Williamson, 2015; Mislevy & Haertel, 2006), the project of E-Rebuild will illustrate an integrative design approach that intertwines learning task development with assessment construction. The selection and construction of game-based learning tasks will elicit the core gaming/learning actions that operationalize the targeted competencies and serve as both the source and evidence of competency development. The game log is developed to capture these actions, with the logged data parsed as the values of observables (variables) in a competency-based statistical model (e.g., Bayesian networks). The sequencing and accumulation of a collection of tasks (or game levels) then need to support both learning progression and the accumulation of evidence for stealth assessment.

### *2.2.4 Designing Game-Based Learning Supports*

A main challenge of designing games is that their consumption (by players) is relatively unpredictable (Hunicke, LeBlanc, & Zubek, 2004). For an educational game, the interaction between the player and the coded game system is even more dynamic due to the anticipated learning interactivity. Differing in their prior competency status, learning and gaming preferences, and dispositions toward the subject matter and gameplay, players will differ in their reactions and behaviors in a game-based learning system. Apart from learning game mechanics and user interface, the players may be involved in shortcut solutions rather than expected learning actions (Butler, Andersen, Smith, Gulwani, & Popović, 2015), or they may fail to be purposive or mindful to generate theoretical thinking from game tasks and actions.

Therefore, support for game-based learning should be designed to not only reduce the entry barriers (e.g., via training) but also enhance the opportunities of intentional learning and knowledge acquisition during gaming for diverse learners. Game-based learning support can be tool- or material-mediated support embedded in the game or external, human agent-mediated support arranged as part of the game-based learning environment. The design efforts focus on exploring what, when, and how learning supports are integrated and presented during gameplay to foster task and action engagement and performance for knowledge acquisition.

## 2.3 Chronicle of Iterative Design, Testing, and Refinement of E-Rebuild

E-Rebuild creation is a heavily iterative design process. There are more than 100 published versions of the game, with either major or minor revisions in between these versions. Below we present a design chronicle recording major developments and revisions associated with E-Rebuild. Iterative player testing was conducted during and across the following design phases.

1. Starting exploring the action of building: In the original version of a build, dragging objects around with the mouse in a top-down view was the only control mechanism. The objective was to fill a certain percentage of the given space with shipping containers. The containers were little more than rectangular prisms. After a given time limit, the space would shake to simulate an earthquake. If the same amount of containers remained, the level was passed. The objectives were to quickly simulate an earthquake, track occupied space, and enable container manipulation in a three-dimensional space.
2. Designing interface of site surveying and collection: In our next iteration, we decided a fixed view offered limited flexibility and experimented with a first-person view that would offer the freedom to explore the world and give the player a sense of presence. Moving items would happen by picking them up. The player would approach an object, press a key, and carry the item with them. We also introduced a "stamina" meter to stop the user from carrying items forever. This was a great improvement from the previous version but not without compromise. Where the previous iteration required only mouse movement and a single click, the new control scheme was inspired by the WASD control scheme. This added a total of six keys and constant mouse control. For experienced gamers, this may be second nature, but experienced gamers do not comprise the totality of our target demographic (Fig. 2.1).
3. Designing alternative modes of gameplay, controls for building, and initial game world: After switching to keyboard and mouse movement, we doubled down on the controls. Items could be held from a distance, and then they moved following the player at the distance they were picked up. Using another pair of keys, the player could move the object closer to or farther from the player. An earthquake was simulated on the platform shown in the mini-map. To complete the level, players should move a certain number of containers to the platform and maintain a given height after the earthquake (Fig. 2.2).

A toolbar was added to control many options. A number of tools were available. These included marking tools (such as freehand, line, rectangle, and ellipse) and shaping tools, (such as cutting and scaling). We began working on the beginnings of the building mode of E-Rebuild. The view was static with an unmoveable camera. This became an issue when working in three dimensions (Fig. 2.3).

At the same time, we started to explore game world design by experimenting with larger environments that appeared to overwhelm players with the opportunity

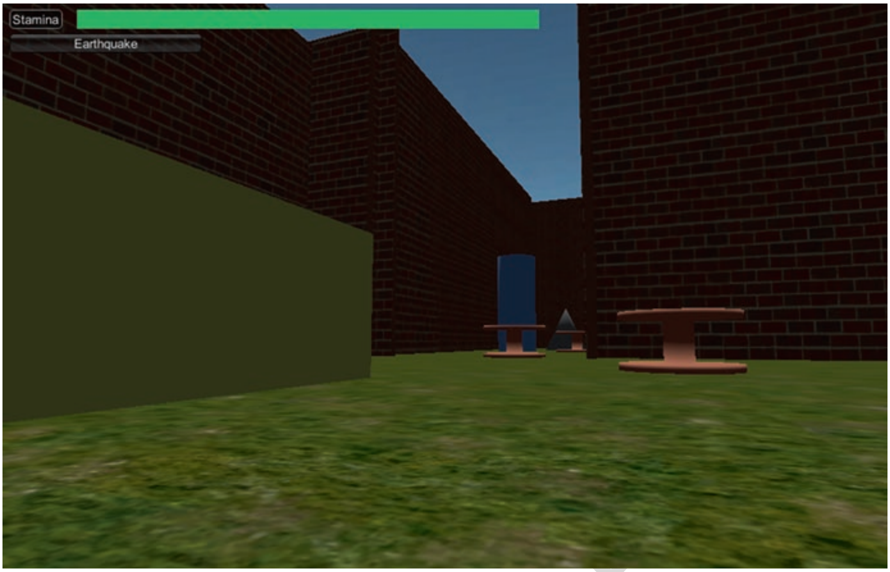



**Fig. 2.1** Earliest prototype with the basic item-movement control and a stamina meter


**Fig. 2.2** Alternative perspective of play and basic controls

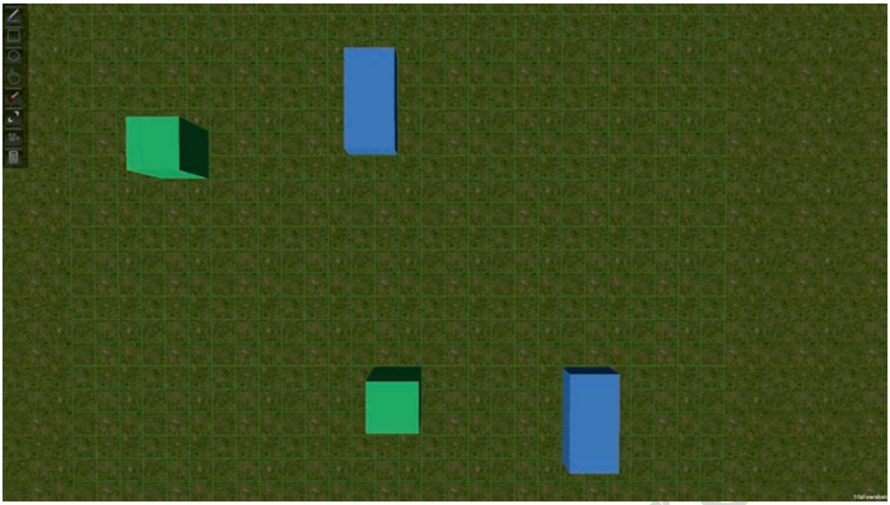
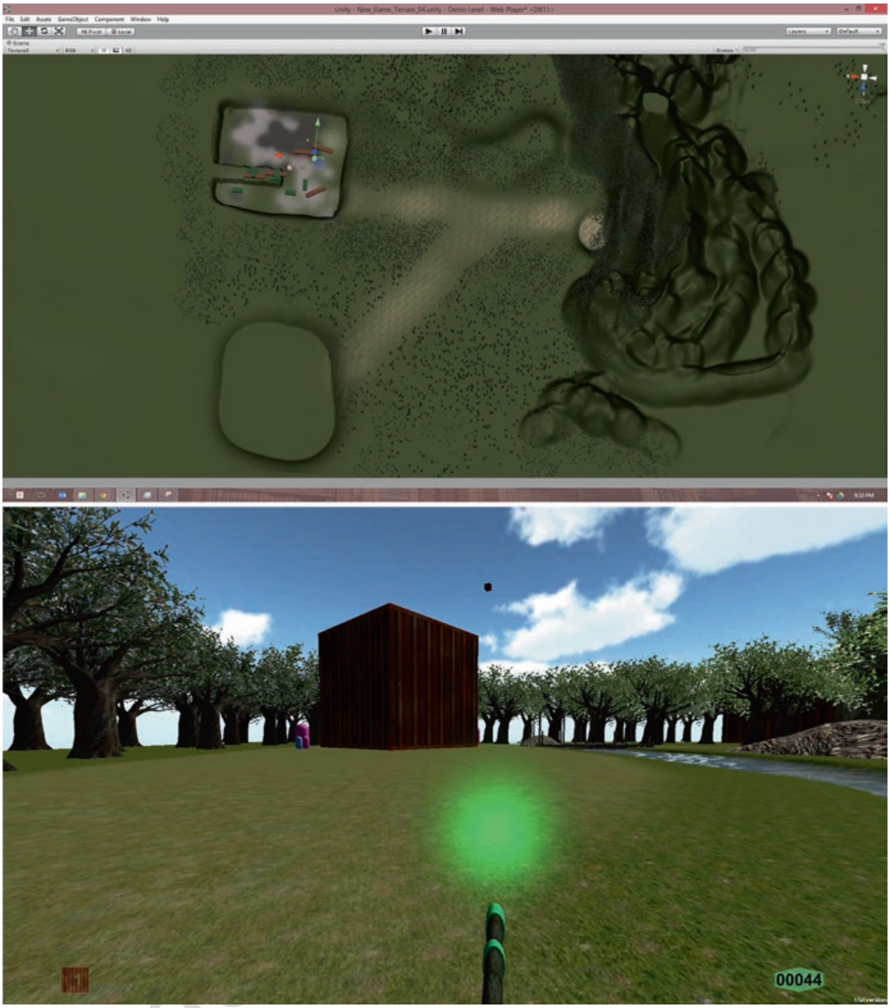


**Fig. 2.3** A tool bar was added

to explore. We settled on a somewhat middle ground—a smaller island. This island remained the basis for the island episode for a number of iterations, which was also the beginning set of the adventure mode of E-Rebuild. In the adventure mode, the player was to explore the area and collect items via a magic wand that made a green "poof" as the item was collected and subsequently disappeared. Collected containers were marked on the bottom-left corner, while additional resources collected were given as credits on the bottom-right corner (Figs. 2.4 and 2.5).

4. Designing the allocation action, creating the initial game level with the reward mechanism: A family allocation objective was added. Blue capsules were used as placeholders for people (families). The island people had three states: lost, found, and assigned. Collecting and allocating families into the shelter increased happiness credits, which gave the game three classes of credits: time, resource, and happiness. These can be seen on the bottom right (Fig. 2.6).
5. Refining the design of the initial game level: To enable (family) allocation inside a structure (e.g., a container), we refined the collection interface so that players could switch their wand from collecting a whole structure to only collect its parts (e.g., panels). This also allowed the player to make windows and entryways in the structure. The building and adventure modes were integrated in a single level: Players could toggle the mode by pressing 0 (zero). In the initial level, the player would collect and place containers to rebuild a row house and then assign the families into the house (Fig. 2.7).




**Figs. 2.4 and 2.5** Initial island for the adventure mode of gameplay

6. Developing additional in-game learning supports: An in-game scratchpad was designed to allow users to make quick notes and conduct calculations. Two dimensions (2D) of the target structure (e.g., the row house) and site landmarks were added to assist the player in building the structure. An issue remained unaddressed: it was difficult for the players to get out of the water when they were distracted and explored the underwater land (Figs. 2.8 and 2.9).


**Fig. 2.6** The first game level

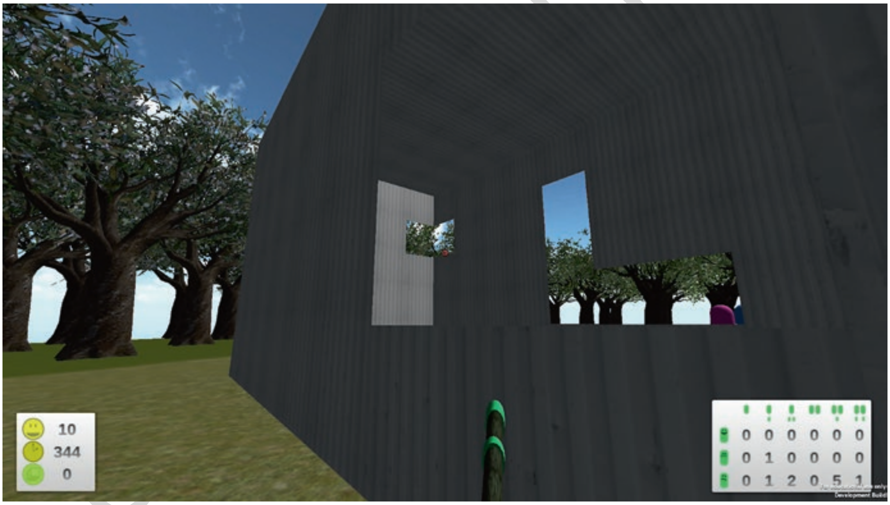



**Fig. 2.7** Adding an allocation action

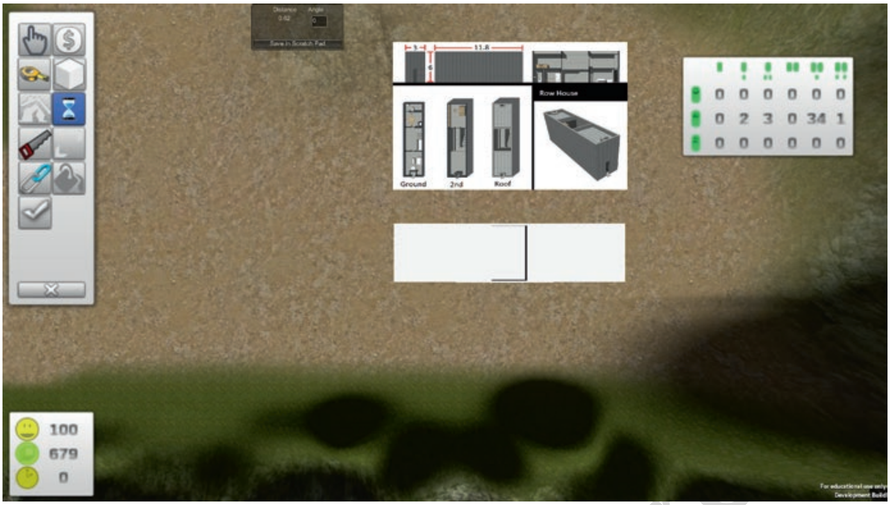



**Fig. 2.8** Adding in-game learning supports

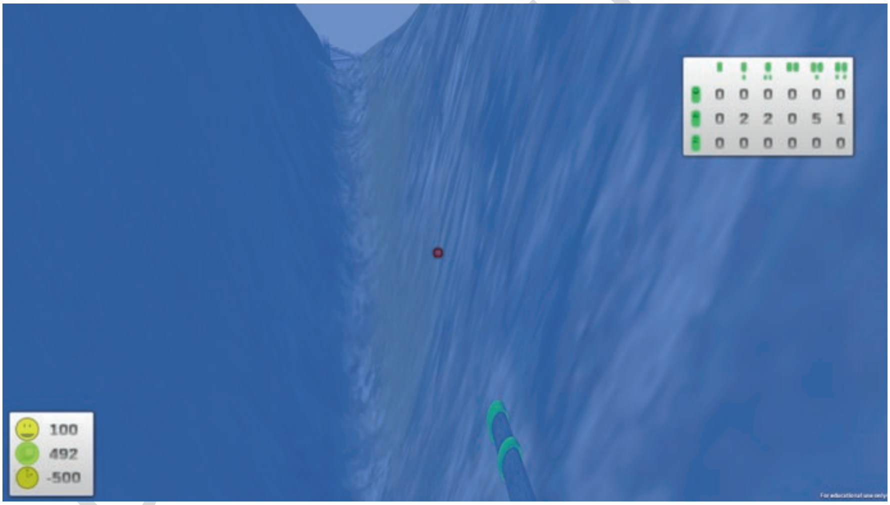



**Fig. 2.9** Getting stuck under the water


**Figs. 2.10 and 2.11** Chunking the task

7. Chunking the task in the game level: The task is a complex multistep problem that has many steps that could stop the player from progressing. We tried chunking the task or game level into sub-goals to guide the player, with a progress bar showing the distance to the goal. A tutorial level was also created to train the player on game controls (Figs. 2.10, 2.11, and 2.12). AU2
8. Designing another game level featuring the building action at a higher granularity degree and a trading action: With an initial in-field testing study completed, we began to design the desert level that features the building action at a higher granularity and complexity level (e.g., via adobe blocks rather than containers) and a different scene/setting (i.e., a desert). We also added a training action (in AU3

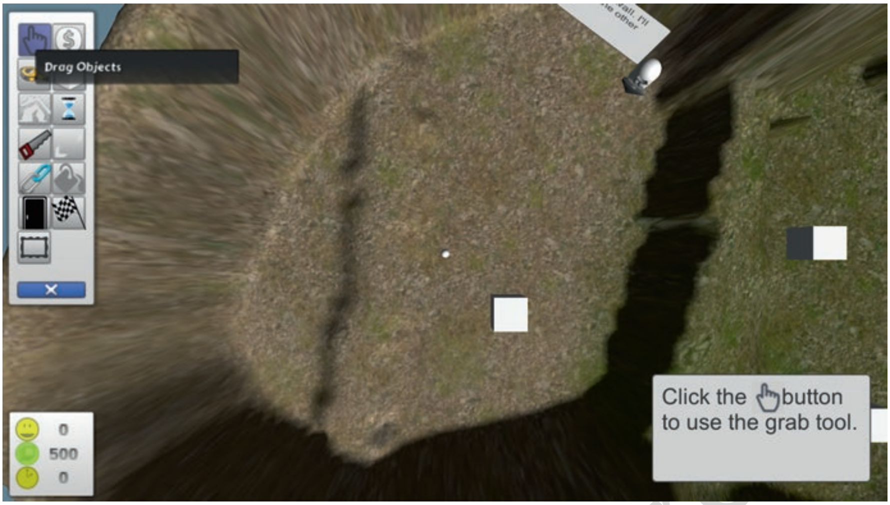



**Fig. 2.12** An initial tutorial level

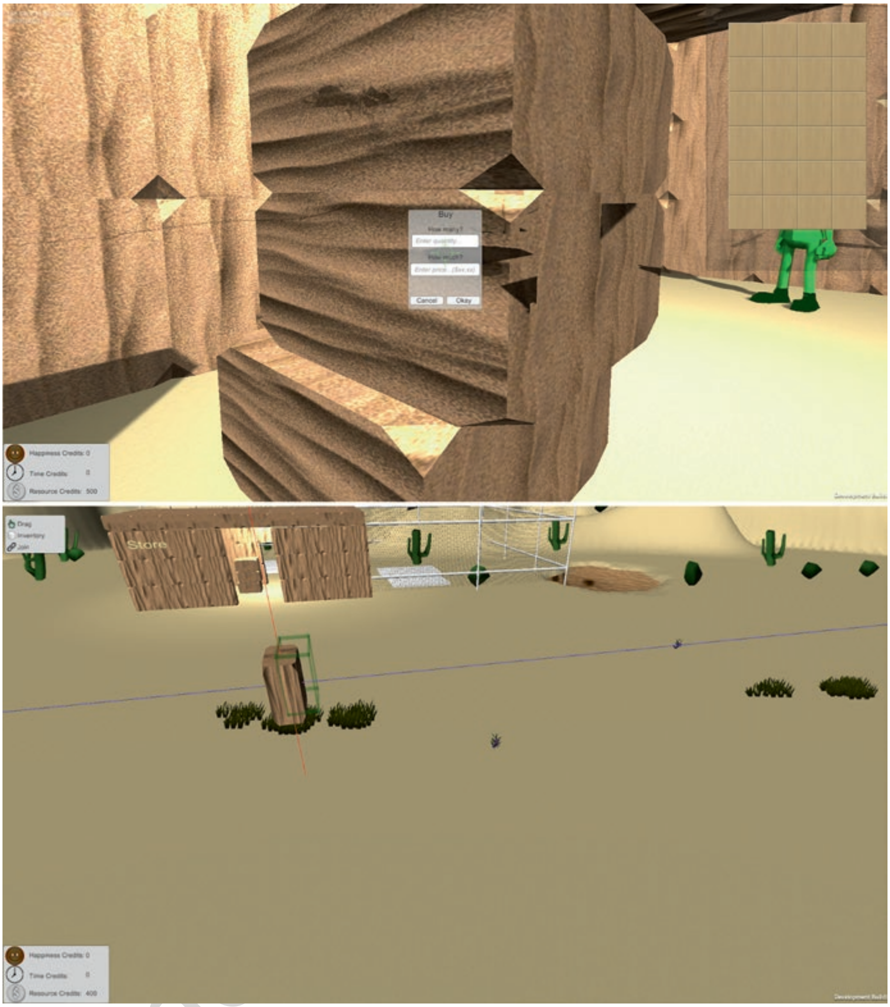


addition to the collection action) with the building materials. Considering the game world exploration issue, we designed natural boundaries such as a sandstorm, a fence, and tall bluffs to the desert set to keep the players on the construction site without wandering away (Figs. 2.13 and 2.14).

9. Refining the interface of the trading and building actions: We refined the user input interface of the trading action to necessitate cost planning and calculation by the player. In the original movement control of the building action, the item movement followed the cursor, but items would easily overlap with each other and cause a popcorn effect. To fix this issue, we changed the movement control so that the player moved the objects along the two displayed axes that can be changed by moving the camera around the object. Items actually moved on a variable-sized grid. The actual location would be with the green outline when the player decided to place the item (Figs. 2.15 and 2.16).
10. Expanding the "desert" and "island" episodes with levels (tasks) development: Both episodes were expanded with tasks (levels) development. As more levels became available, an episode tab became more useful. The episode tab of the menu gave a wide overview of the tasks for this landscape. The task tab gave specific instructions for completing each level. As the levels and game grew more complex and longer in duration, a way to save was necessary. Originally the saves were all local. This forced the user to use the same computer from session to session. Levels with variant difficulty options were given to the user. This difficulty selection was associated with variables and their dependencies in a task, the number of problem-solving steps involved, and the complexity of the embedded mathematical competency. To assist with problem-solving, an interactive problem-solving help section was added. Levels were also even more discreetly chunked with more frequent performance feedback (Figs. 2.17, 2.18, and 2.19).


**Figs. 2.13 and 2.14** Adding a “desert” level featuring building at a higher granularity level

11. Adding a “school” episode and more levels: A school set was added as an urban environment in which complicated building tasks, such as classroom and stadium stands building, were developed (Figs. 2.20 and 2.21).
12. Creating cohesive UI: A new UI was created to be cohesive across the game episodes. The new version opted to use the level chunks as smaller individual levels, each with a single task to complete with a number of constraints (or obstacles). This version also saw the immersion of adventure and building modes—the player does not need to shift between the two modes through a toggle but has a “fly” mode that fully integrates ego- and exocentric perspec-




**Figs. 2.15 and 2.16** Trading action and the item movement control

tives in the virtual game world. The interface of the collection action was updated to require action-related mathematical reasoning. The end-of-level, textual performance review was replaced with a visual, star system. The player profiles were associated with game user names to help organize their gaming logs (Figs. 2.22, 2.23, 2.24, and 2.25).

13. Creating a cohesive game world and a new "farm" game episode: The level set design was updated to be consistent across game episodes. More levels/tasks were added throughout the game, including a "farm" episode, to better support the learning and assessment of mathematical competencies specified (e.g., ratio


**Fig. 2.17** "Desert" being a multi-level game episode

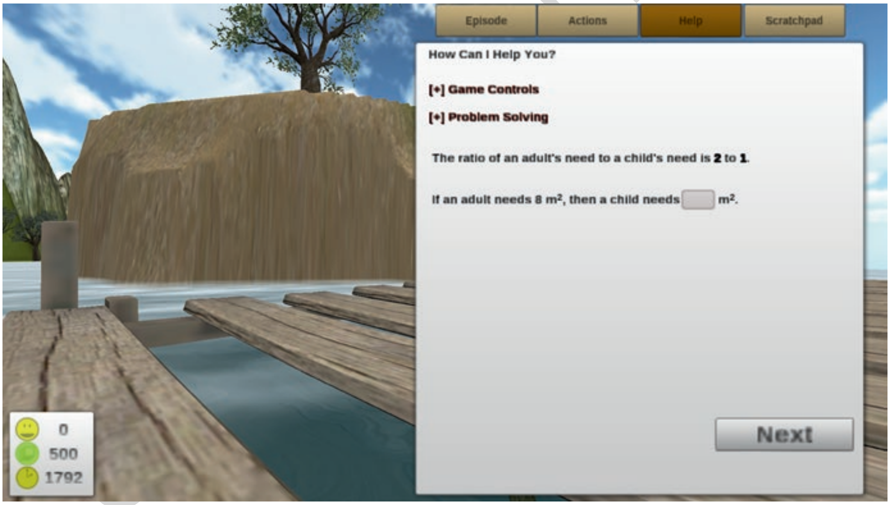



**Fig. 2.18** Interactive problem-solving help


**Fig. 2.19** End-of-level textual performance feedback

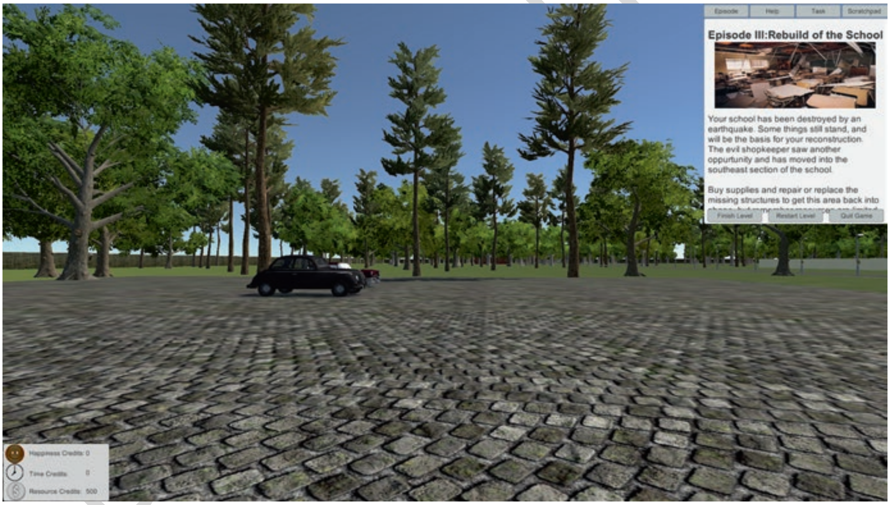



**Fig. 2.20** Adding a school episode

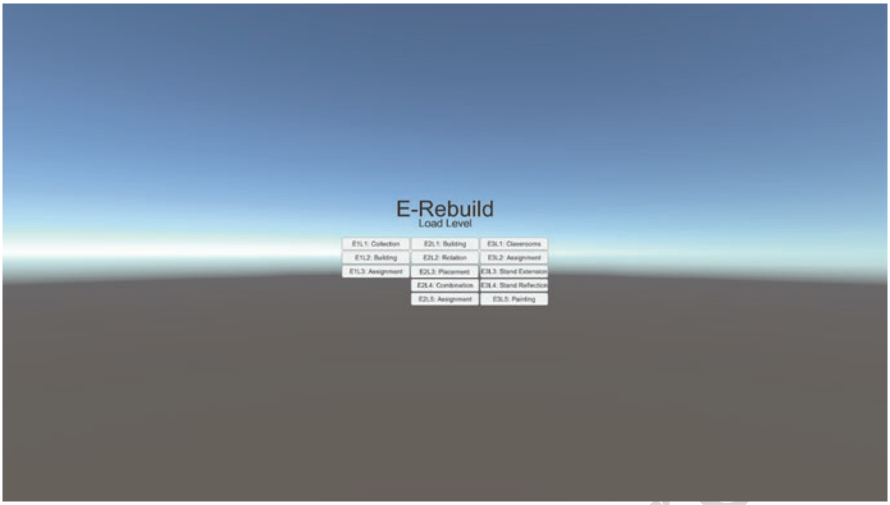



**Fig. 2.21** Being a 3-episode and 13-level game


**Fig. 2.22** A new cohesive UI


**Fig. 2.23** Intermediary interface of the collection action


**Fig. 2.24** A visual, 3-star system as the end-of-level performance feedback

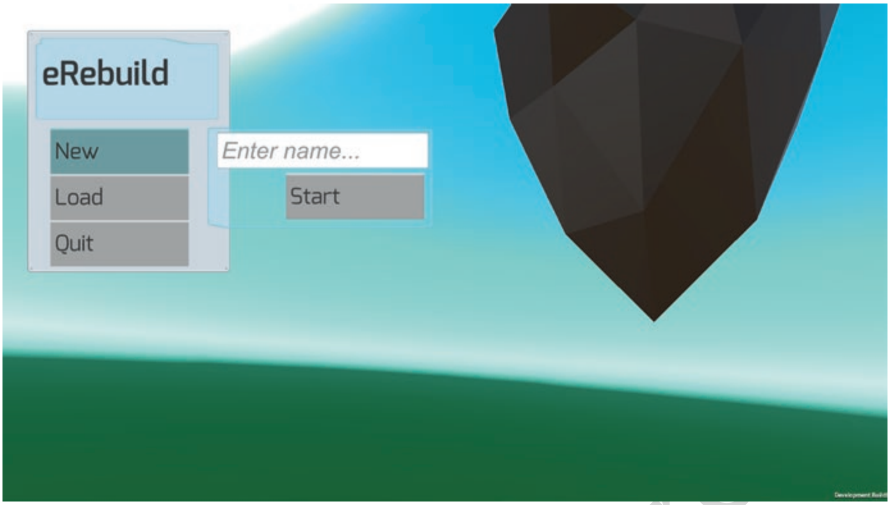



**Fig. 2.25** Player profile associated with a game user name for log organization

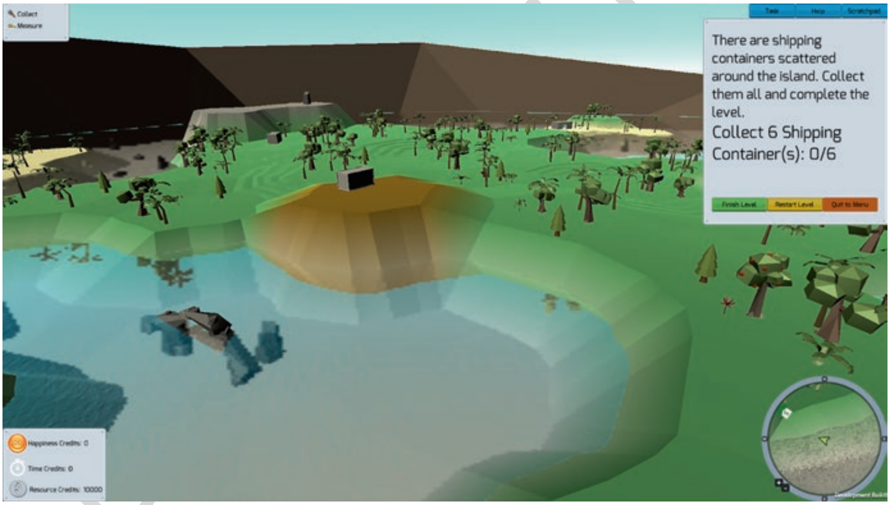



**Fig. 2.26** A cohesive game world: Island

and proportion, composition and decomposition of shapes, and transformation of geometric shapes, angle, perimeter, area, volume) while presenting a gradual learning progression. At this point, the game had 19 levels in 4 episodes (Figs. 2.26, 2.27, 2.28, 2.29, and 2.30).

14. Updating the game reward with a badge system and the UI to foster cognitive interactivity: The three-star system did not provide enough information to the payers on their game-based mathematics problem-solving performance. To

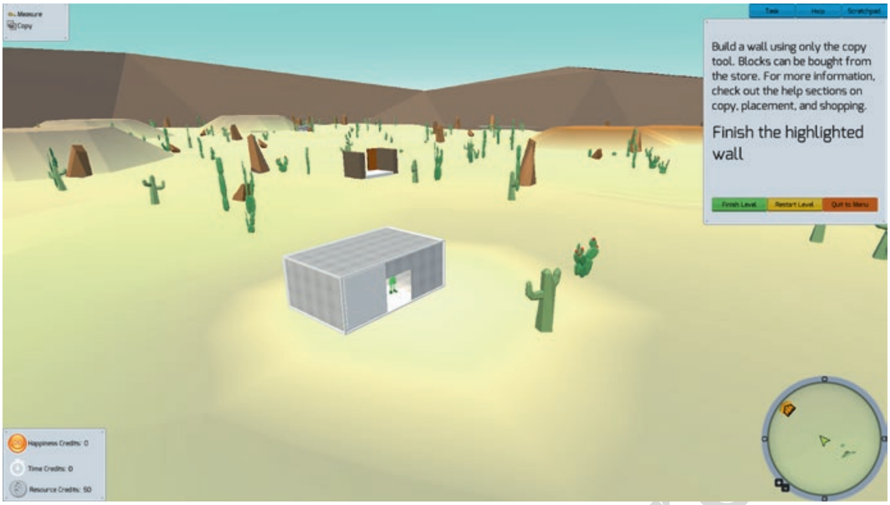



**Fig. 2.27** A cohesive game world: Desert

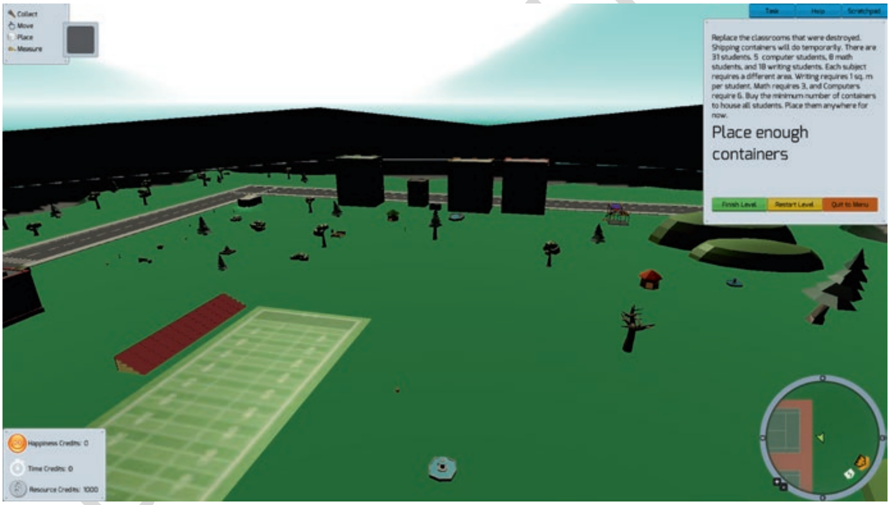



**Fig. 2.28** A cohesive game world: School

promote reflective inquiry, we used a multi-badge system to provide more detailed feedback on different aspects of the game-based problem-solving performance (e.g., fluency, accuracy, and thriftiness). We also refined the user interface again to increase cognitive interactivity. For example, in the collection action, related object information was presented as a tooltip in tables or charts. The log-in was moved to the server to allow online play on Chromebooks (Figs. 2.31, 2.32, and 2.33).

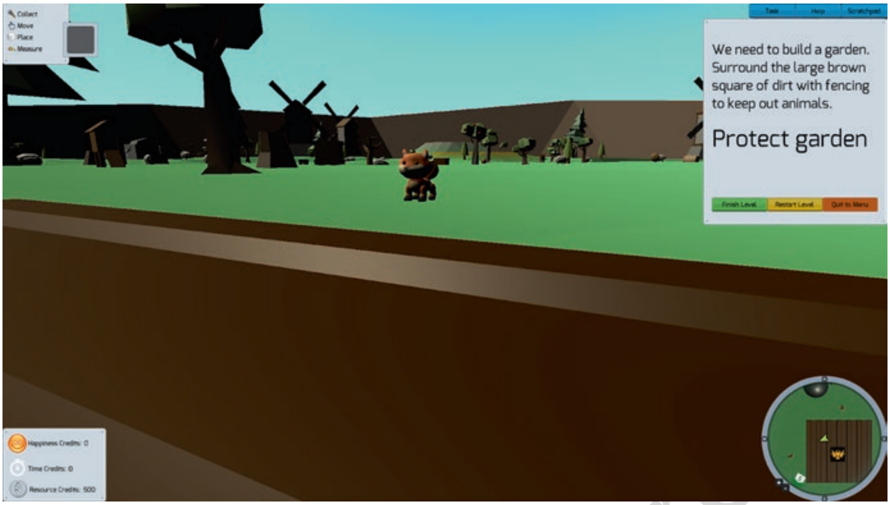



**Fig. 2.29** A new episode: Farm

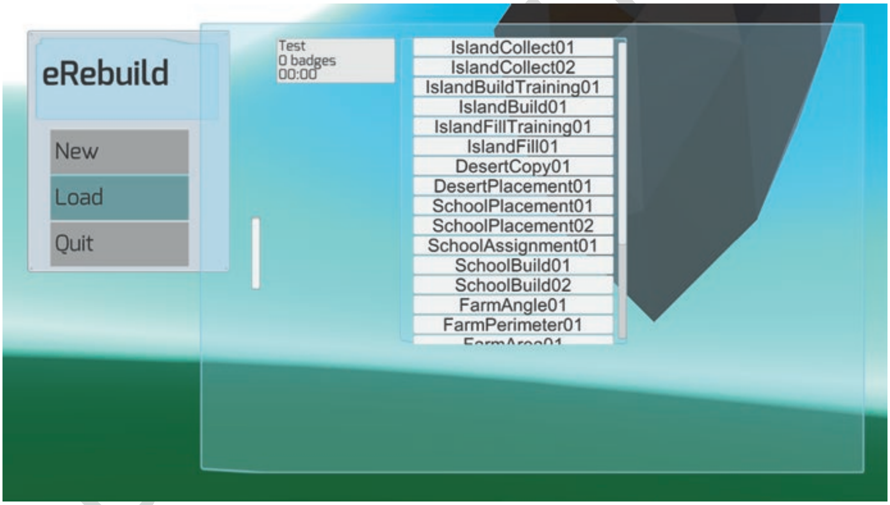



**Fig. 2.30** Being a 4-episode, 19-level game


**Fig. 2.31** A badge system


**Fig. 2.32** Support for cognitive interactivity in the collection action


**Fig. 2.33** Online login

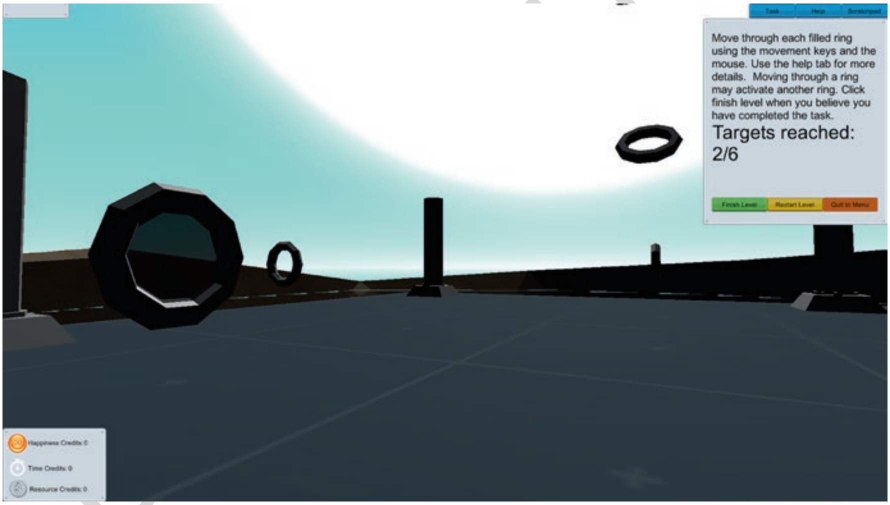



**Fig. 2.34** New training levels

15. New training levels and the movement interface: To better reduce the entry learning curve and the technical functionality of object maneuvering in a 3D space, we added more training levels and designed a new item manipulation system. The new system provides unobstructed views on the item's three-dimensional movement to allow easier manipulation and a higher level of responsiveness. At this point, the game had 43 game levels distributed across 4 game episodes (Figs. 2.34, 2.35, and 2.36).

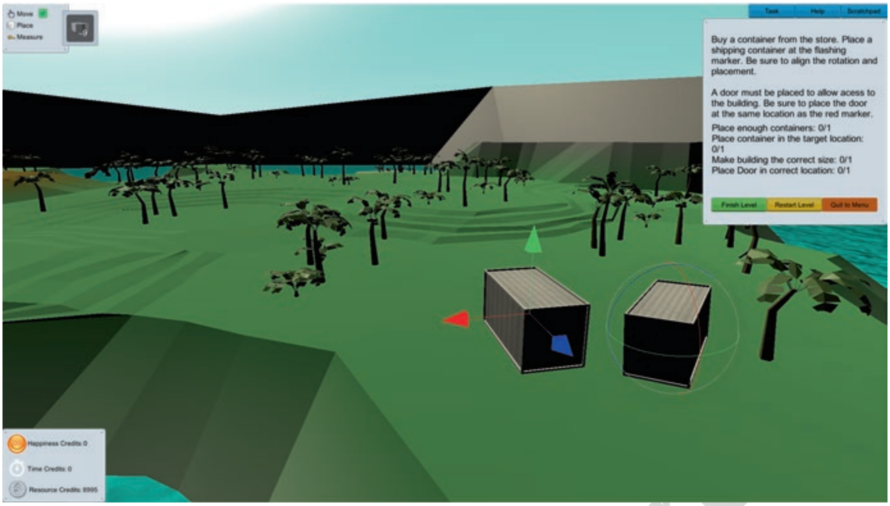



**Fig. 2.35** New movement interface

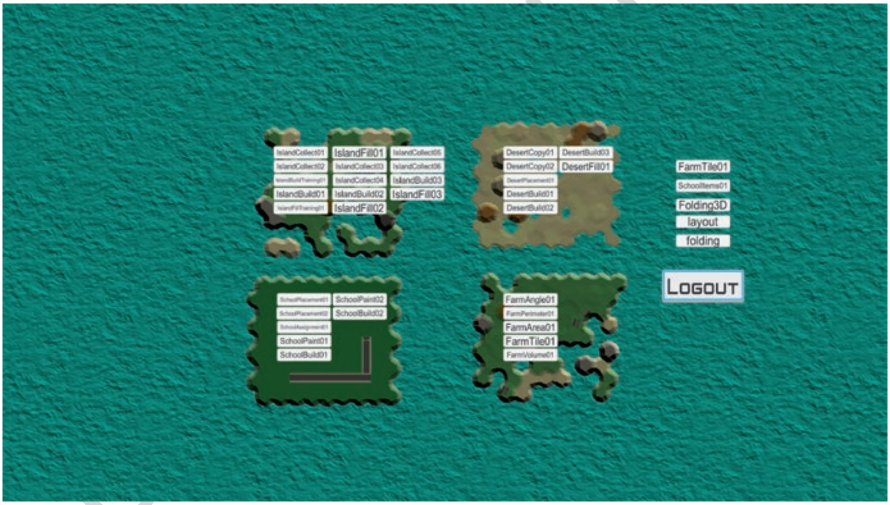



**Fig. 2.36** Being a 4-episode, 43-level game

In comparison with the iterative revisions in the gameplay and level development, the game logs have remained relatively stable after the core game actions are specified. This allows for comparison between the older logged play data and the new ones, as well as the refining and validation of the statistical model for stealth assessment. Where the game has gotten more complex, the logs have become simpler during the development process to allow for quicker parsing of data and smaller file sizes.

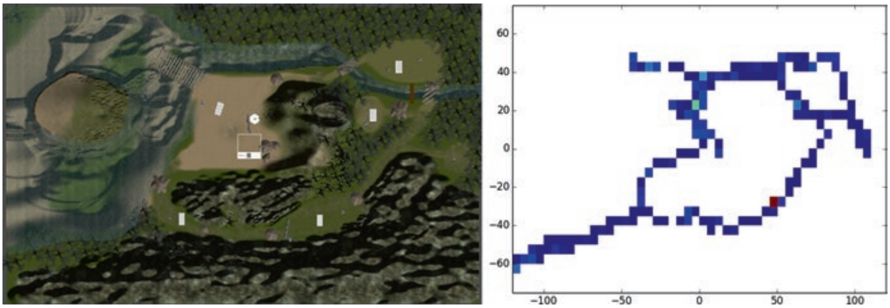



**Fig. 2.37** Heat map analysis example

Originally, nearly everything was logged. The player's position was recorded approximately once per second to allow for a heat map analysis of their paths, as you can see in Fig. 2.37. This required an xml block similar to:

```
<Auto Position>
 <runningTime>2.009376</runningTime>
 <Position>(-29.0, 0.8, 42.1)</Position>
 </Auto Position>
```

The log files were flooded with the above entries, which caused problems with file size and parsing, as well as reading them in a glance. In the next revision, we removed the auto position recordings. Still, nearly every action was recorded. The log files (see Fig. 2.38) were more manageable but still required parsing to get to the variables we used in the Bayesian network. We then further trimmed the log structure to only include what we would use in the statistical model. The logs (see Figs. 2.39 and 2.40) then varied by level but could be interpreted in a glance.

## 2.4 Researcher Positionality and Reflection Notes

As Van Manen (1990) pointed out, our preunderstandings predisposed us to interpret the nature of the phenomenon in a phenomenological inquiry. As part of the effort to bracket these predispositions, we presented a brief introduction of our roles in the design team as well as a reflective description of individual perspectives and perceived experience of the interdisciplinary design process for game-based learning platform development. Our motives, domain-specific backgrounds, and habits of and dispositions toward design certainly impact our reflective analysis of the design process and the findings that emerged as they are part of the lens brought to the project. However, it is important to understand that these preunderstandings did not remain unbracketed during design and research. Additionally, the authors applied peer debriefing and member checks in the inspection and rectification of the data and interpretations.

**Fig. 2.38** Refined game log example 1


```
<?xml version="1.0" encoding="utf-8"?>
<root>
  <Switch Mode>
    <Mode>adventure</Mode>
    <runningTime>7.54639769</runningTime>
  </Switch Mode>
  <Buy>
    <Name = >Foundation38</Name = >
    <Quantity = >1</Quantity = >
    <Offered Price = >60</Offered Price = >
    <Overpaid = >0</Overpaid = >
    <runningTime>45.5761337</runningTime>
  </Buy>
  <Switch Mode>
    <Mode>menu</Mode>
    <runningTime>60.98643</runningTime>
  </Switch Mode>
  <Switch Mode>
    <Mode>adventure</Mode>
    <runningTime>64.99804</runningTime>
  </Switch Mode>
  <Switch Mode>
    <Mode>menu</Mode>
    <runningTime>68.62134</runningTime>
  </Switch Mode>
  <Switch Mode>
    <Mode>adventure</Mode>
    <runningTime>73.5573</runningTime>
  </Switch Mode>
```


**Fig. 2.39** Refined game log example 2


```
<?xml version="1.0" encoding="utf-8"?>
<root>
  <Name>Jonathan Norton</Name>
  <Level>26FamilyPlacement</Level>
  <Time>73.36515</Time>
  <NumWrong>0</NumWrong>
  <AssignmentComplete>true</AssignmentComplete>
  <MaterialCredits>800</MaterialCredits>
</root>
```


**Fig. 2.40** Refined game log example 3


```
<?xml version="1.0" encoding="utf-8"?>
<root>
  <Name>Stryder</Name>
  <Level>IslandBuild02</Level>
  <Time>485.3943</Time>
  <NumBlocks>6</NumBlocks>
  <NumTrades>2</NumTrades>
  <TotalLost>-326</TotalLost>
  <MaterialCredits>9350</MaterialCredits>
  <Distance>4.17769</Distance>
  <Size>0.50826925</Size>
  <Angle>1.15756774</Angle>
  <BuildingComplete>false</BuildingComplete>
  <LevelComplete>false</LevelComplete>
</root>
```

### *2.4.1 Fengfeng Ke*

> My belief is that mathematics is a way of thinking, and learning is to develop powerful ways of thinking.

**Role and responsibility in the design team** I am the principal designer of the E-Rebuild project and responsible for leading all facets of the design and research work, including the design, in-field testing, and refinement of E-Rebuild, the management of the project team’s communication and collaboration, as well as the data collection and analysis. As an associate professor of educational psychology and learning system designer at the Florida State University, my design and research interests lie in digital game-based learning and innovative learning environment design. Besides E-Rebuild, I have participated in multiple other research projects on game- and simulation-based interactive learning systems.

**Personal goal or interest for the E-Rebuild design** As a former gamer, I prefer games that involve puzzle solving and construction. As a teacher and a lifelong learner, I believe learning is ultimately self-regulated, and teaching is a process of instilling thinking or lifelong learning skills. These dispositions are naturally infused into my vision for the E-Rebuild design. As a learning system designer, I think the vital role of technologies for learning is not offering an alternative delivery media or a motivation tool but facilitating a new way of understanding and organizing learning. My goal for designing E-Rebuild is hence not creating a single digital learning tool but using it as a test-bed to examine and refine our conjectures of mathematics and learning, to experiment with previous hypotheses governing the integration between learning and play, and to discern new tools and methods to designing an active, meaningful learning experience.

**Perceptions of interdisciplinary design of E-Rebuild** Designing a learning system is naturally an interdisciplinary process. During previously designed projects, I have worked with content experts, educators, developers, and evaluators from different fields. These works, however, were more multidisciplinary than interdisciplinary, in that the design and development efforts of team members are frequently segmented by time (e.g., the evaluation won’t start until the functional prototype is ready) or by a clear-cut responsibility division. In spite of the occasional brainstorming or peer debriefing opportunities, the overlapping or truly collaborative design efforts in those projects are usually limited. E-Rebuild project, differently, is an extensive and longitudinal project that requires and allows for a full understanding of the discipline-specific subcultures, a gradual development of project-specific design culture, and iterative testing of interdisciplinary perspectives and methods in the design artifact. In spite of the numerous discussions of generic principles of interdisciplinary collaboration or professional development, I have found the interdisciplinary design of E-Rebuild, by itself, is a learning by doing process. In our earlier project meetings, I felt less comfortable or occasionally lost with the team communications; I wondered whether and how those lengthy interdisciplinary communications would be a worthy investment to the quality of the final artifact, given a tight project schedule. All these uncertainties, however, got addressed once the mutual understanding of the language, stances, and concepts were achieved and when we gradually found our protocol to channeling differing interests and expertise into the tangible working plan.

**Perspectives of interdisciplinary design and research for educational game development** In spite of a plethora of research on game studies, designing an educational game, like art, is an utmost ill-structured problem. Intuitive design, modifying a worked example, trial and error (or design experimentation), and working backwards (e.g., an analytical or evaluative review of exemplary games to inform the current game design) are frequent strategies adopted by educational game designers. Designers, educators, or evaluators may have an overarching goal or vision about the desirable game-based learning experience, but it is difficult to operationalize such an experience as tangible objectives. Even when objectives are set, the problem space for achieving these game design objectives is murky. Through conducting and reporting a reflective and phenomenological analysis of the core facets and salient patterns emerged from a longitudinal design project, I hope our work will help to illustrate and better define the problem space of interdisciplinary education game design.

### *2.4.2 Valerie Shute*

Measure twice and cut once!

**Role and responsibility in the design team** My role in the E-Rebuild project is primarily related to all assessment-related aspects of the project. For a brief background, I am the Mack and Effie Campbell Tyner Endowed Professor of Education in the Department of Educational Psychology and Learning Systems at Florida State University. Before coming to FSU in 2007, I was a principal research scientist at Educational Testing Service where I was involved with basic and applied research projects related to assessment, cognitive diagnosis, and learning from advanced instructional systems. My general research interests hover around the design, development, and evaluation of advanced systems to support learning—particularly related to the twenty-first-century competencies and STEM content. My current research involves using games with stealth assessment to support learning—of cognitive and noncognitive attributes. As the originator of the term and technologies surrounding "stealth assessment," I'm pleased to see it become more broadly accepted and used in new research projects (including this current one).

**Personal goal or interest for the E-Rebuild design** When we began thinking and talking about this project, prior to funding, our goals were to design a platform that integrated architectural design and building with evolving and deepening mathematical understanding. Moreover, this was to be designed and developed in the context of a game with which kids would want to engage and learn. For the past 4 years, and across a lot of iterative pilot testing, our original goals are successfully being met. With regard to the assessment part of the story, we have focused on refinements to both the local and server-side game logs as a way to capture relevant gameplay data to inform the math competency model (developed at the onset of the study). Concurrently, we continue to explore the viability of other data mining approaches to supplement the stealth assessment within E-Rebuild. Together, the more top-down (theoretically driven) stealth assessment approach coupled with the more bottom-up (empirically driven) data mining approach should provide more accurate estimates of competency states than either alone. And having more accurate estimates—available at any time and at various grain sizes—will provide the basis for more targeted and effective math learning supports in the game, including the automatic selection of the next best task to provide to the learner based on his/her current needs.

**Perceptions of interdisciplinary design of E-Rebuild** Our weekly meetings of the entire interdisciplinary team have been, overall, enjoyable and interesting. Because everyone has their own areas of expertise, it is often a very educational experience as well. Furthermore, when a topic is discussed, multiple perspectives are available to look at an issue from all sides. Communication is respectful, even when there are differing views on solving a particular problem.

We also have been able to integrate "lessons learned" from other currently funded and directly related research. For example, in one of our current National Science Foundation (NSF) cyber-learning grants using stealth assessment within a game called Physics Playground, we needed to come up with some difficulty indices in order to rate the various levels in the game relative to their difficulty. Originally, we had derived indices related to particular aspects of the level (e.g., if there were a lot of obstacles in the problem that made it harder, and so on). However, we soon realized that additionally considering the nature of the physics content related to the game level was necessary to make decisions about "level difficulty" overall. The information gleaned from the cyber-learning project has thus been used in the current E-Rebuild project. That is, we have developed an approach in E-Rebuild to categorize all of the various game tasks based on a difficulty index that consists of both (1) the complexity of the problem representation and solution processes in a given level and (2) the mathematical competencies required in the solution, as well as prerequisite relationships between the competencies and sub-competencies. This in turn has engendered the development of an adaptive game-based algorithm, which can select appropriate learning tasks based on the real-time estimate of a learner's competency profile to support the development of focal math knowledge and skills.

**Perspectives of interdisciplinary design and research for educational game development** In summary, working within an interdisciplinary design team has been a great experience. As mentioned, because of the varying areas of expertise, I never leave a meeting without learning something new (and often multiple new things). The discussions of issues among the team members have resulted in an expansion (and occasionally a refinement) of different areas given fresh eyes on a problem. What has been most enlightening to me is the direct relationship between architectural design processes and math skills, at a general level. So in a sense, success in the game provides a two-for-one—gaining architectural designing and building skills and associated math knowledge and skills. Another eye-opener is what takes place when we take our game into the schools. Invariably, the teachers and importantly the students have a lot to share with regard to the functionality of the game. Both teachers and students are very clear about what they want and need to succeed—as designers of new levels (teachers using the platform) or as players of the game (students).

### *2.4.3 Kathleen M. Clark*

A view from a non-gaming, non-assessment, mathematics teacher educator.

**Role and responsibility in the design team** I have just completed my 31st year in mathematics education. I began teaching mathematics in 1987 in an inner-city Miami high school. I taught mathematics in a variety of public schools in Florida and Mississippi until 2001, when I was awarded an Einstein Distinguished Educator Fellowship. During the 1-year fellowship, I worked in educational policy for the US Senate, and though I did not return to my secondary teaching career afterward, I decided to pursue my doctorate in Mathematics Education at the University of Maryland. I have been at Florida State University (FSU) since August 2006. Early in my FSU career, my research focused primarily on pre-service and in-service mathematics teachers, with an emphasis on the role of history of mathematics in mathematics teaching and learning. I currently spend the majority of my time conducting research on the use of primary historical sources in the teaching of undergraduate mathematics.

My role on the E-Rebuild team is to serve as the "mathematics education expert." In this role, I focus on providing support for the mathematical content both within the game itself and within the various forms of assessments used in the project. The content that informs the game and the assessments were—in the first development of E-Rebuild—based upon the Common Core State Standards for Mathematics (CCSS-M). However, as the game has developed, we included attention to the Florida Mathematics Standards (FMS), and we do so because the game is currently and primarily tested with Florida mathematics teachers and students, and we must be cognizant of the minute differences between CCSS-M and FMS.

**Personal goal or interest for the E-Rebuild design** I was initially drawn to the E-Rebuild project—particularly from the students' perspective—because I often observe limited appropriate use of multimedia tools (e.g., appropriate web tools, electronic or Internet-based games, computer software, etc.) to promote middle grade students' learning of mathematics. I was excited by the potential of E-Rebuild as a means by which students would learn or, possibly practice, not only core mathematical concepts (e.g., ratio and proportion skills, properties of geometric shapes and determining their area, perimeter) but solve problems in a contextually rich and meaningfully engaging game environment.

My experience with the E-Rebuild game itself has been one of healthy skepticism. I have never been a gamer, so this may contribute to my skepticism, at least to a small degree. That said, I find myself thinking about the numerous variables that have the potential to impact the student learning experience as they play E-Rebuild. For example, are the directions clear for the student in each game level? Is the game visually and structurally appealing to young learners? What are the connections that students make with regard to the mathematical concepts that they meet in the game? What does the context and gameplay environment contribute to students' engagement with mathematical ideas? In my observations of student gameplay, I have noted a high level of student frustration from the perspective of game design features and not from the perspective of mathematical content. Thus, this prompts me to think about how little expertise I have with regard to game-based learning—or educational games in general—because I wonder about the amount of unproductive struggle students experience with game features and how this may detract from the role of productive struggle when solving the mathematical problems imbedded in the game. And, due to my lack of expertise in "stealth assessment," I do not understand how the components of these more affective experiences with E-Rebuild may factor in to whether students are learning as a result of their E-Rebuild play.

**Perceptions of interdisciplinary design of E-Rebuild** I have participated in a number of interdisciplinary projects. I continue to be energized by the way in which experts and practitioners from different disciplines and fields come together to create, design, and test instructional tools (e.g., curriculum, materials, interventions) to promote student learning. There are several meeting structures used within the E-Rebuild project: Some are focused specifically on design of tasks, levels, and episodes that comprise the game itself. Other meetings are focused on the inherent mathematical concepts, skills, and problem-solving situations at the core of the game, as well as the components of the architectural design elements that contribute to the underlying mathematics. Regardless of the purpose or goal of any given design meeting, I have found the discussions to be interesting, and they challenge me to try to find ways in which I can learn as much as possible while also drawing on my mathematics education background in order to contribute in optimal ways.

I believe the most challenging aspect of the design meetings has been navigating the various communication styles within the group. We often assume we have "taken-as-shared" knowledge, and since we do not, it often takes us several iterations to operate with the same (or at least similar enough) knowledge. I have always taken my own notes during the numerous meetings in which I have participated over the years (though I often felt I was the only one—perhaps because I was the only one who needed to!), and these have been helpful in being able to feel that I can keep up with the various aspects of the E-Rebuild work. I think that consistent use of agendas and assigned tasks for regular meetings would have been beneficial. For example, by scheduling and planning specific tasks and agenda items, I believe a more equitably distributed range of ideas and foci would be addressed in the meetings.

**Perspectives of interdisciplinary design and research for educational game development** I am intrigued by the notion of what we can learn from the development and the use of educational games in the learning of mathematics. I think there is much more that we can know (and, consequently, contribute to the field) with respect to student learning and E-Rebuild gameplay. However, as a qualitative researcher, I believe that we must continue to conduct student and teacher interviews to better understand the student experience with E-Rebuild. Additionally, the various teacher experiences are an important part of this inquiry. Students have played E-Rebuild as part of the regular mathematics classroom activity, in non-mathematics classrooms, and within after school and summer camp contexts. I believe it is wise to investigate the ways in which students have played E-Rebuild in these different formal and informal contexts and work to understand the assessment results with these different implementation lenses in mind. I think there is great potential for the results of these investigations to assist us in focusing on further game design and development to maximize the potential for such a tool to improve middle grade students' nonroutine problem-solving abilities.

### *2.4.4 Gordon Erlebacher*

> In my view, a perfect educational game should improve player skill (in an idealized situation) without the player being aware of the purpose of the game. Not unlike good advertising which influences the actions of a person without that person being aware of the ad.

**Role and responsibility in the design team** The E-Rebuild project team was formed in 2011, and I participated from the onset. My role in this project is to ensure that the team applies sound game design principles during the development of the game and help manage implementation of its game mechanics. Prior to my arrival at FSU, I was a researcher at NASA Langley and at the Institute for Computer Applications in Science and Engineering. During that period, I conducted theoretical and computational research in the field of turbulence. In 2009, I created a first course on Game Design at FSU, which attracts undergraduate and graduate students over a wide range of science and nonscience departments. I have often felt that properly designed games could help students achieve more of their potential and mathematics is a natural subject matter given my background. I am currently Chair of the Department of Scientific Computing at Florida State University, an interdisciplinary department whose mission is to develop computer algorithms with applications in the applied sciences. Since 1996, I have been involved in computational science, developing algorithms in the fields of visualization, GPU programming, flow simulation, and more recently in computational neuroscience and deep learning. Over the past 30 years, I have been exposed to many frameworks, software, computer languages, and technologies, which has helped me develop the skills to interact with researchers in different fields.

**Personal goal or interest for the E-Rebuild design** In the early stages of the project, I envisioned that we would eventually develop an exciting and engaging game that middle-school students would want to play and as a result undergo a gradual improvement of their mathematical skills. The game would adapt to the player, choosing scenarios and tasks commensurate with the player's ability. This would be accomplished through the collection of data (player movement, mouse clicks, imagery) that would then feed into an assessment system that would measure the mathematical proficiency of the player. Together with player history, new scenarios would be generated, adapted to each player. Through a team effort, the game evolved somewhat differently. School teachers would be responsible to creating the scenarios and tasks appropriate for their students, and the players would be aware that the game was meant to improve their mathematical skills. We have been refining the competency model and field-testing the game to validate the model and ensure that the students are indeed improving through gameplay. At this time, my goals are more ambitious. The difficulty of finding enough participants to test the game and model leads to the idea of creating a synthetic player based on machine learning principles with a "brain" that can adapt to gameplay. Although this brain would be a poor facsimile of a human brain, my hope is that it would learn in different ways and at different rates depending on the sequence of tasks and scenes presented, and this would lead to insights into further game improvements. At this stage, this remains just a vision for future research.

**Perceptions of interdisciplinary design of E-Rebuild** Early in the project, after the project was funded, the whole project team met on a weekly basis to discuss the nuts and bolts of the game, such as game mechanics and backdrops, along with some initial tasks the player would have to complete. These meetings were fun but challenging in the early days because of the different backgrounds and past experiences of the participants, which ranged from architecture to educational games to instructional systems to mathematics education to assessment and science computer simulations. Our different past experiences led to rather different ideas on what would go on in the mind of an eighth grader, which in turn would impact decisions related to game development. Discipline vocabulary, which differed between disciplines, also impeded progress on occasion, and it behooved us to allow for difference of opinion which was not necessarily substantive but could be the result of a different understanding of word usage. A recent case in point was confusion in the use of the term "elevation view," which for an architect refers to a side view but to a game designer might mean *view from above* or a *third-person view.* Individual members also had a unique vocabulary, which sometimes/often led to entire discussions when different people used the same word in discussions, but with different meanings. Once, the majority of a meeting was spent debating the meaning of the words *task, scene, objective,* and how to use them to describe different components of the game. Another early discussion revolved around the task of construction; should objects be controlled via the keyboard or using the mouse? How would the player respond to these different choices? How much help should the player be given and in what form should it be made available. Should the help be in-game or out-of-game? Should the game flow be interrupted or should we maintain player immersion into the game. There was disagreement on all of these aspects, which eventually were resolved. The cases that remained open were decided via testing by the students. Overall, I enjoyed the meetings, gaining an appreciation of other fields of study and how they related to ideas presented.

**Perspectives of interdisciplinary design and research for educational game development** Interdisciplinary research and interdisciplinary design are concepts that have been around and promoted for many years. From my personal experience, the E-Rebuild project is probably the most satisfying interdisciplinary effort in which I have participated. Very often, participants meet once a year or biannually and share what they have accomplished since the previous meeting. On the other hand, our whole-team meetings were weekly initially and, more recently, biweekly. All ideas are shared and discussed, and progress made since the previous meeting is presented. I have learned a lot from our interactions, not only in terms of game design but also on the personal level. I have learned to appreciate some of the tools used by architects, educators, and programmers to help others learn and enjoyed the process through which different goals eventually merged into a game that pleased the entire team. Eventually, it became clear that stated goals during our meetings often reflected the background of the person. For example, our architect pushed for a game that was much more architecturally oriented in terms of realism, while others on the team were more interested in gameplay at the expense of realism. Good teamwork produces a game that compromises between these different visions without sacrificing the vision of the team leader. For large projects, a truly interdisciplinary approach is often indispensable, particularly when a game touches upon many different disciplines as it does in our case (construction, education, mathematics, and simulation).



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AU4

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# Author Queries

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| Queries | Details Required | Author's Response |
|---|---|---|
| AU1 | Please confirm the identified head levels are okay. | |
| AU2 | Please confirm the inserted citation for Figs. 2.1–2.36. | |
| AU3 | Please provide better quality artwork for Figs. 2.10, 2.11, and 2.18. | |
| AU4 | Please provide publisher location for "Almond et al. (2015), Giorgi (2009) and Butler et al. (2015)". | |
| AU5 | Please provide publisher name and location for "Hunicke et al. (2004)". | |

# Chapter 3
# Interdisciplinary Design Activities and Patterns

**Abstract** In this chapter, we provide a reflective and analytical description of the interdisciplinary design activities of E-Rebuild, identify driving design questions and salient design patterns that capture and frame the essence of E-Rebuild development, and discuss distilled meta-generalizations that help to decompose the interdisciplinary learning game design processes to inform future work related to design, research, and deployment. The description of salient patterns of interdisciplinary game design in this chapter provides a contextualized design narrative/account of core design processes along with an analytical synthesis of core design pattern elements—a design problem statement with its context and specifics, the solution or technique to solving the stated problem, and the pattern of transferring or scaling this design solution or design move.



## 3.1 Introduction



There has been a growing recognition that the process of designing and developing a computer-supported, highly interactive learning system in general and games or simulations for learning in particular, is by its very nature an interdisciplinary and challenging task. Prior works of design science and serious game design highlight the importance for learning and game designers to record, identify, and distribute not only detailed, contextualized design narratives but also higher-level, distilled design knowledge such as *design patterns* (Pratt, Winters, Cerulli, & Leemkuil, 2009; Winters & Mor, 2008).

A design pattern is a high-level specification for a solution methodology to a design problem, by specifying the particulars of the problem and highlighting recurring solutions that are field tested in real-world application development. In this chapter, we provide a reflective and analytical description of the interdisciplinary design activities of E-Rebuild, identify driving design questions and salient design patterns that capture and frame the essence of E-Rebuild development, and discuss distilled meta-generalizations that help to decompose the interdisciplinary learning game design processes to inform future work related to design, research, and deployment.



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The design meeting notes, sketches, aids, paper and electronic prototypes, as well as conversation emails during the E-Rebuild project have all been archived. Iterative and reflective interviews were also conducted among design team members. Adopting the phenomenological qualitative research approach (Moustakas, 1994), we have conducted a thematic analysis to explore salient themes or patterns that capture the nature and features of design choices and actions by the interdisciplinary design team. While coding salient themes emerging from the data, we have also referred to the prior research in the field of design science when seeking the boundary and meaning of a theme or pattern. The description of salient patterns of interdisciplinary game design in this chapter provides a contextualized design narrative/account of core design processes along with an analytical synthesis of core design pattern elements—a *design problem statement* with its context and specifics, the *solution* or technique (with its key structure or mechanism) to solving the stated problem, and the *pattern* of transferring or scaling this design solution or design move.

During the design of E-Rebuild, a variety of driving questions or problems initiate the negotiation of the design plans and the coordination of the design knowledge among interdisciplinary team members. It then takes interdisciplinary cases/examples exploration, infield testing, and iterative refinement for the team to settle on a design solution. Moreover, design leadership during the decision-making takes on an important role in the project management, especially within a constrained timeline.

## 3.2 Core Design Patterns and Activities

### *3.2.1 Defining the Design Goal: A Trinity of Architectural Simulation, Mathematical Learning, and Gaming*

**Problem statement** During the initial design meetings of E-Rebuild, interdisciplinary team members debated and went back and forth to better understand E-Rebuild as "an architectural simulation game for math learning." Some notable selections from the debate include statements such as: "Should it be mainly an architectural building simulation that provides an architectural design education while embedding mathematical conceptual development at the same time? Should it focus on the representation of mathematical concepts and problems, with architectural scenarios being a meaningful context for mathematical representation? Or should it prioritize the gameplay and fun elements situated in the practice of architectural and mathematical puzzle solving?" These debating topics, in general, revolve around an innate design problem for learning game creation, *What is the creative stimulus or the ultimate inspiration for the creation of E-Rebuild as a trinity of content learning, simulation, and gaming?*

**Exploration of the design solution** The aforementioned design problem roots in the typical challenge of designing a learning game—to integrate learning into core game elements while not violating or corrupting what is enjoyable about games (Garris, Ahlers, & Driskell, 2002; Ke, 2016). Prior research argued that the prospect of using a game to motivate learning lies in the assumption that this game will involve learners in what is fundamentally engaging about the subject, via either a dynamic representation or the simulation of the most "fun" (dynamic) component of the academic domain (Ke, 2016). Yet it remains debatable as to whether and how pursuing "fun" or gameplay as the preliminary design inspiration will drive the unified representation and simulation of content and content-relevant epistemic practice. For example, the following design notes documented a design goal motivated primarily by the gameplay exploration:

> *We will start by building a "Block" level in which the player will select, drag, and drop the "block" object to build a specific architecture form. The process is somewhat akin to a 3D version of block stacking or jigsaw game – the player must "fill up" an empty, 3D architect using the building blocks (i.e., revive a building). Task assessment proceeds by testing whether and how much the destined 3D architectural space has been occupied, whether this constructed 3D architecture will collapse with a shaking landscape, etc. The embedded math concept can be geometric shapes, area/perimeter, and transformational geometry (rotation, reflection, and dilation), which can be integrated with the organizational principles of architectural design (such as symmetry or balance, hierarchy, and rhythm).*

The notes portray a design inspiration that seeks a gameplay that can unify or align with mathematical content and math-related architectural practices. Such a gaming-driven design exploration, however, has been found by the content experts and instructional designers in the team as incapable of capturing the depth and multifaceted nature of content learning. It prioritizes certain mathematical competencies or levels of learning (e.g., composing and decomposing geometric forms for conceptual understanding) while ignoring the others (e.g., problem-solving that involves area, volume, or unit rate computation).

As an alternative and refinement, the team shifted toward domain content and architectural design as the dynamic starting points. In particular, we started by developing graphical competency models to outline the structure or typology of targeted mathematical competencies. Each node in the math competency model represents a performance objective and highlights learning actions. Exemplary mathematical context problems for each node were also gathered. The practice of composing child nodes or decomposing a parent node along with their supporting mathematical problems has helped us conceptualize varied tasks or quests with corresponding actions within the game (Fig. 3.1). AU2 AU3

Meanwhile, by referring to a pre-developed *Architecture and Children Pilot Curriculum* by Dr. Anne Taylor (our architecture and design education expert in the team), we drafted an *Architecture Terms and Principles* document that gathers basic architectural concepts and skills that may relate to mathematical thinking.

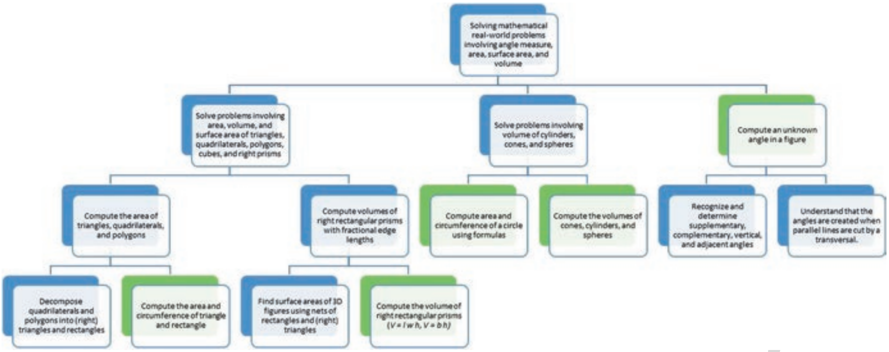



**Fig. 3.1** An example of graphical, competency models

This 24-page working document, illustrated in Figs. 3.2 and 3.3, provides definitions and descriptions with rich visuals and real-life examples. Similar to the mathematical competency model, this manual also highlights the componential performances and actions when synthesizing the skills architects and designers depend on. Given these features, this manual has worked as a handy manual to frame not only the task development but the game world and object design in E-Rebuild.

The simultaneous exploration of the targeted subject domain and content-relevant epistemic practices has helped the project team better delineate the design problem space—an externalized representation of the multifaceted design goal of E-Rebuild. Given this clearly defined, action- or performance-themed design problem space, the team then began anew and were productive in searching, selecting, and assembling the necessary gameplay components (e.g., core actions, rules, and backdrop missions) to further frame the design goal and the problem space from a "gaming" perspective.

**Design pattern summary** Defining the design goal of the simulation-based learning game is the delineation of a multifaceted, interdisciplinary design problem space. The framing of the problem space is initiated by a synchronized modeling of domain-specific competencies and the cataloging of simulated epistemic practices. Modeling and cataloging should highlight the fundamental performance expectations and supporting actions for content representation and practice simulation. The competency-driven, action-themed design problem space will then drive the exploration and selection of gameplay that captures and unifies content learning and simulated epistemic practices.

**TABLE OF CONTENTS**


1. THE ORGANIZING PRINCIPLES OF DESIGN
2. GEOMETRIC FORMS IN ARCHITECTURE
3. ARCHITECTURAL VOCABULARY – STRUCTURES
4. SPATIAL RELATIONSHIPS
5. DESIGN AND VISUAL VOCABULARY
   (a repetitive process for design)
6. LANDSCAPE DESIGN
7. SKILLS ARCHITECTS AND DESIGNERS NEED AND USE

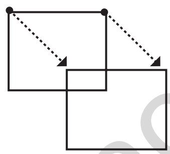

## 2. GEOMETRIC FORMS IN ARCHITECTURE

**Point (Zero D) -** a precise location or place on a plane; usually represented by a dot.

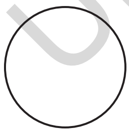
**Line (1D) -** a geometrical object that is straight, infinitely long and infinitely thin.

**Plane (2D) -** a flat surface that is infinitely large and with zero thickness.

**Volume (3D) -** volume is the measure of the amount of space inside of a solid figure.



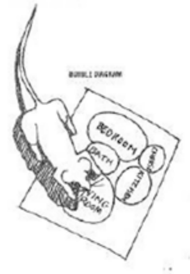
**Circle -** a2 -dimensional shape made by drawing a curve that is always the same distance from a center.



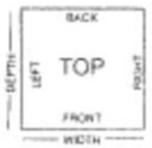
**Sphere -** a3 -dimensional surface, all points of which are equidistant from a fixed point.

**Figs. 3.2 and 3.3** Table of content and example pages of the “Architectural Terms and Principles” document

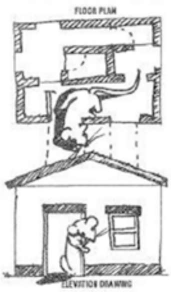
**Bubble Diagram** - spatial relationships; circles or "bubbles" which represent spaces and relationships.




**Plan View** - an overview of a site or building as if a bird were flying over it.




**Elevation View** - front, sides, rear; the front view of an object such as a house front.




## 7. SKILLS ARCHITECTS AND DESIGNERS NEED AND USE

Problem solving process…thinking

Inquire – Define the problem---Problem seeing

Synthesize pull together details

Analyze information

Integrate variables

Conceptualize – create a conceptual vision of a solution to a problem

Abstract – Levels of a solution, conceptual, logical and physical

Visualize – Be able to draw by hand or computer

Formalize – Define and architectural specification to communicate an idea

Communication- Visual-verbal presentations using technology or not

Enable – User's guide. How to use the architecture

Post Occupancy Evaluation – Did the design work or not and by what criteria

Technology Literacy – GPS, Sketch Up, Auto CAD and more

**Figs. 3.2 and 3.3** (continued)

### 3.2.2 *Setting Core Gameplay: Meaningful Mechanics that Connect to Intellectual Learning and Artifact Design*

**Problem statement** The subsequent design question that receives considerable discussion takes the form, "What will a player *do* in the game, and why is that engaging and intelligent?" In other terms, what and how will the core game mechanics of E-Rebuild connect intellectual content and architectural design to motivate and guide math conceptualization and problem-solving? Prior research suggests that learning occurs only when play experience connects to intellectual content; yet the process that leads the attainment of an integral and continuing relationship between gameplay and the content to be learned remains murky (Habgood & Ainsworth, 2011). Moreover, there had been some divergence within the E-Rebuild team as to the share of (architectural) design knowledge relates to mathematical one to be embodied and activated by the gameplay actions and rules.

**Exploration of the design solution** We have reviewed exemplary design cases in relevant disciplines and explored discipline-specific inquiries or tasks when selecting the core game mechanics of E-Rebuild. The discipline-specific design cases and ideas were typically presented by a discipline expert, reviewed and commented on by the team at design meetings. Shared and prominent ideas emerging from these reviews and discussions were then aggregated to be paper prototyped as the initial version of gameplay.

Treating architectural design as the epistemic practice of mathematical conceptualization and problem-solving, the team started by listing the key elements and actions of architectural design and those of mathematical reasoning. The team also searched for architectural design and construction cases that inspire the selection of salient actions for intellectual gameplay, as illustrated by the following design notes documented after several rounds of architectural design case discussion.

*Can we simulate the "building block" and landscape-management design ideas from the New Zealand earthquake rebuild project (https://www.psfk.com/2012/12/shipping-container-mall.html)?*

- *Building blocks (tools: math tools, design tools, building tools, shape/texture).*
- *Building actions: Navigating/exploring, drop/drag/customize, watch/predict/reflect, drawing and modeling (outside the game or using mixed reality)?*
- *Building tasks (reflecting a bottom-up approach, integrating Anne's ideas and content in the Architecture and Children Pilot Curriculum):*

  *Architectural floor plan design—Bubble diagram and a related task: Designing a fast food vegetarian restaurant (spaces only, without equipment) with pre-design exercise (such as decorating a shoe).*

  *Structure in architecture (arch, triangle, asymmetrical* vs *balanced) and a related task: Building a space frame structure for the roof of the picnic shelter with pre-design exercise* (e.g., *toothpick puzzles).*

*Form in architecture or architecture in nature (may involve measurement, data interpretation, scale, and proportion) and related tasks: Using organic structures in nature in a "fantasy" architectural structure for the "moon," with pre-design puzzle (scavenger hunt for basic geometric shapes and forms in nature) or designing a "people's" bridge across the canyon to build a jogging and bike path (designing and modeling natural, beam, suspension, or arch bridges).*
*Visual design, creative design.*
*Landscape, city planning.*

- *Building tasks (reflecting a top-down approach).*

*Building blocks and site planning—Using given building objects (*e.g.*, shipping containers) to complete the construction of a site (*e.g.*, a village). This exercise involves the organizational principles of design (*e.g.*, Symmetry, Balance, and Proportion) and a basic understanding of the geometric concepts of shape and transformation (*e.g.*, reflection, rotation, and dilation).*
*Reference: Architectural Ordering Principles (document is uploaded to the project site)*

| Architectural system | Math system | Gameplay element |
|---|---|---|
| *Primary elements:* Point, line, plane, volume | *Geometry:* 1D to 2D to 3D shapes Area, perimeter, and volume | Reviving an architecture demolished during earthquake—*Jigsaw game*: Recomposing an architectural structure via the scattered elements/pieces |
| *Properties of forms:* Shape, size, color, texture Position, orientation, visual inertia | *Geometry:* Shapes Area, perimeter, and volume *Proportion* | *Scavenger hunt game:* Collecting building items in varied forms and properties |

As the above design note portrays, a real-life post-quake rebuild story, including architectural building elements, actions, and tasks, have driven and inspired the selection of applicable types of gameplay. In addition, a purposeful exploration of the association between architectural and mathematical elements leads to the selection of gameplay that helps unify the math learning and architectural building actions.

On the other hand, the learning system designers and game programmers in the team were concerned that the performance of certain architectural building elements, such as creative and visual design or landscape and city planning, were not only beyond the scope of the design goal but also hard for the digital gaming system to gauge. There was also a concern that a variety of differing game mechanics derived from the simulation and representation of varied architectural building tasks and principles would lead to a lack of focus and consistency in gameplay and hence diminish engagement. Instead, members of the team proposed that only one or two gaming actions be deployed, as suggested in the following design note:

> *A player is given a set of materials and must create a structure. Performance is evaluated in the game by the number of waste materials left over, time to completion, and structural soundness of the structure. Peers can also rate the aesthetic beauty/originality of the structure. There can be several constraints in E-Rebuild, such as 1) amount of materials, 2) strength of materials, 3) weight of materials, 4) variety of materials, 5) time, or 6) building specifications. Let's take constraints 1 and 4. In this case, assume that the player is given 1000 cubic feet of oak wood and 100 square feet of glass. Based on these constraints, the player must decide how to build a house.*
>
> *This game design corresponds to a* measurement *core mechanic. A person must* create a blueprint *of the structure that will be used to* cut *the materials to be used for the structure. This blueprint specifies the dimensions of every element in the structure. A player sketches a blueprint with a pencil and paper outside the game. With the blueprint created, the player enters every unique component (e.g., material, quantity, dimensions) of the structure into a menu within the game. An exemplary entry might take the form: wood board, 50, 2 X 4. The material is always determined by the materials given in the problem (wood, glass). Then the game automatically "cuts" the materials. I do not think the player should cut material as this would get very tedious and repetitive. Once the materials are cut to size, the player must* assemble *the materials using the mouse and the blueprint.*

In this design proposal, the core game mechanic is measurement, which consists of the secondary mechanics of structure planning/sketching, material cutting, and material composing. The core gameplay rules are design constraints such as efficiency, thriftiness, and soundness. These ideas support simplicity and intrinsic content integration. Yet the practice of a major gaming action (e.g., blueprint sketching) outside the game world may lead to the interruption of game flow. The menu input for the cutting action led to a "design" action that felt like a mathematical drill that was tedious.

By integrating the aforementioned two interdisciplinary perspectives, we decided to focus on three core architectural design actions and constraints that identify and unify the most dynamic processes of architectural building and mathematical reasoning and are in-game play. These core actions included (a) gathering materials (including site surveying, material collection, and transformation), (b) crafting (measurement + cutting), and (c) building (with given design constraints, evaluated according to thriftiness and sturdiness). These core actions and rules defined the first version of E-Rebuild, which was prototyped, user tested, and evaluated based on the feasibility, playability, and learning-necessitating potential. After iterative prototyping and user testing, the material crafting action was later replaced by a material-trading action; an allocation (of space) action was added later.

**Design pattern summary** Gameplay exploration consists of identifying gaming actions and rules that (a) discern and unify the most dynamic and engaging processes of the performance systems to be simulated, (b) are feasible (e.g., being actuated and assessed in the game), and (c) are streamlined and scalable (to compose diverse tasks or scenarios). The gameplay exploration is driven by sharing, reviewing, and aggregating interdisciplinary task examples and design cases. A purposeful mapping of the association between applicable game mechanics and the design cases/tasks proposed, along with the subsequent prototyping and user testing, will then help to classify and consolidate the game mechanics.

### *3.2.3 Design Constraints for Rebuilding: Evaluating and Rewarding Performance in the Game*

**Problem statement** A design inquiry related to the exploration of gameplay defines the evaluation of gaming success. Some team members argued that players require flexibility with their design tools and goals, while others pointed out that specifying design constraints and measurable rules is critical for computerized assessment of a design artifact in the game. A variety of relevant questions arose during the team discussion: What are the success criteria for post-quake rebuilding? Restore (replicate) the pre-quake structures/models or withstand earthquake in different magnitudes? Should the rebuilding task be accelerated given a forthcoming earthquake, or self-paced with the option of testing the structure with an earthquake simulation? Do we want to do computerized or peer evaluation? What will be the design constraints and performance evaluation criteria?

**Exploration of the design solution** For the inquiry of rebuilding performance evaluation, the architecture and scientific computing experts led the team in a document research and case review of the earthquake architecture. This exercise contributed a list of factors that mediate the challenging nature of a building task (in terms of sturdiness of the structure against the earthquake vibration), including the types of earthquake (and hence the necessity of designing diverse support structures) and other associated design parameters (e.g., liquidation issue of the terrain). After the initial prototyping and user-testing of the earthquake architecture, we found that simulating all these factors was not only time-consuming but also led to learning challenges far beyond the targeted competencies. For example, creating an anti-earthquake building would require a player to define the center of mass of a composite structure and calculate friction. Evaluating the collapsed objects to gauge the structure's sturdiness is also tricky. For example, it is difficult to define the degree of "collapsing." What would be the consequence if the structure only has one layer and hence would only rotate or move instead of falling down given the earthquake vibration? Given all these design considerations, the team decided to focus on structure/model rebuilding rather than building anti-quake structures.

In the initial design phase, the team could not persuade each other and hence came to a compromised decision that we would enable both approaches of evaluating a gamer's design performance: (1) computer evaluation based on the structure or functionality of the architecture (e.g., whether the architecture will collapse with shaking, how much the site space is filled and used efficiently) and (2) evaluation by peers on the organizing principles and/or art/beauty of the architecture (e.g., peer critique, or design-protocol-based, portfolio-based evaluation), which can promote reflection on action. Yet with a clearer definition of the design goal in the later phase and after more elaborated discussion on the logistics and training required for implementing peer evaluation with middle-school students, the team collectively decided to drop the peer evaluation idea.

By synthesizing the reviewed cases and documents, the architect and learning environment designers in the team co-proposed a list of the design parameters acting as the performance evaluation standards for E-Rebuild gameplay. These parameters then drove the design of the game reward mechanism, as the following figure illustrates (Fig. 3.4).

**Design pattern summary** The gameplay rules, which involve mainly the evaluation of game performance and the game reward mechanism, are confined by the success criteria of the simulated epistemic practice and the predefined design problem space. Research of the exemplary cases in the subject domain will contribute evaluation rules that are aligned with the authentic performance success, while the review of the predefined design goal and prototyping along with infield user testing will help to delimit goal-oriented and feasible rules.

### *3.2.4 Design Execution: Grounding Ideas in the Computer Game System*

**Problem statement** The execution or implementation of design propositions via a computer game engine involves grounding and concretizing sketchy ideas related to the user interface, tools, functions, interactive objects, landscape, logging structure, narratives, and scaffolds/aids. The processes and end products that result from developing these game system components are interdisciplinary in nature, conveying and testing varied interpretations by the team members of game-based and



**Design Parameters**

1. Thrifty in money and time (a & b)
2. Sustainability and sturdiness (c1)
3. Addressing specific, current human's needs (c1-3)
4. Scalability or Expansion to address expected, higher-level human's needs (c1-3)

**Gameplay Awards/Constraints**

a) Material credit (limited materials or resources)

b) Time credit (limited time - the risk of next earthquake hit)

c) Living (Human's needs)

  1) Survival (i.e., Morbidity) with physiological needs (shelter, breathing, food, water, and sleep)
  2) Security (in body, property, and resources)
  3) Social (i.e., belonging) - community

**Fig. 3.4** Design parameter and game reward mechanism architectural design-oriented learning engagement. These salient design execution processes in E-Rebuild evolved around a series of prompting questions or debatable perspectives, such as the following:

- How will the player actually move materials around? What is the most intuitive interface for rotating, stacking, and customizing (e.g., cutting and scaling) objects? What exemplary interface mechanisms can act as a reference?
- Avoid text entry, if possible.
- Will "model sketching?" be handled from within or outside the game environment? Or should we make a set of model sketches (simulating real models from Google Earth via Google SketchUp) available to the player and then perhaps have the player construct model sketches at advanced levels?
- How will NPC characters be designed? For example, should we embed a "mini-me" avatar of the player to promote identity development and improve understanding of the proportion concept?
- Is it possible to embed an artificial intelligent agent who can scaffold game play emotionally and cognitively?

Given the above questions, the teams' perceptions varied and could be characterized as four discipline-related dispositions which prioritized, respectively, (a) intuitiveness in gaming interactions and hence an increased opportunity of game engagement, (b) motivated practice of mathematical reasoning and computation, (c) increased opportunities for (architectural) design thinking, or (d) sufficiency and quality of evidence collection to drive game-based learning assessment. These diverse perspectives triggered lengthened, controversial discussions on the format of a user interaction widget (e.g., numerical value entry, or multiple choice, versus scrollbar), granularity or fidelity level in the simulation of core design actions (e.g., building, model sketching) in relation to the prospect of facilitating math or design learning, the design of game world and objects, the proportion and framing of narratives in the game world, the approach of logging and assessing gaming actions, and the approach of embedding in-game support (e.g., background help versus active prompts).

**Exploration of the design solution** The uncertainty in the design execution of E-Rebuild was resolved and settled via iterative design prototyping, expert review, and infield user testing. Feasibility, learnability, and playability are three integral, yet sometimes controversial, facets to be balanced when we gauged and settled on game development details.

***The interaction interface for core gaming actions*** (e.g., to build item maneuvering) was debated in relation to whether activating physics during the building actions would be beneficial or disruptive to gameplay and learning engagement. On the one hand, positioning, stacking, and rotating 3D physical objects are more challenging than maneuvering nonphysical ones. With the physics law activated, objects can bump off each other, fall down, and crash the structure. Thus, building a structure becomes a carefully planned and precisely executed series of actions and movements. Such an interface has created a learning curve and a reduced sense of autonomy for game players, especially those not used to 3D gaming. On the other hand, simulating the authenticity of the building process is a natural part of an architectural simulation game. We also observed that by decreasing the intuitiveness of object maneuvering interaction, the game has made it compulsory for a player to engage in planning their building movements (e.g., where to position each item and how to rotate it precisely for stacking) and hence reinforced their spatial and geometrical reasoning. Besides, adding a "snapping together" feature to the stacking function has made layering an object on top of another more efficient. In other terms, the team compromised on a trade-off and purposeful integration between learnability and playability during the gaming interface development.

Another example of compromise appeared in the decision to adopt a numerical value entry, rather than the choice button or scrollbar, for user input. The human-computer interaction, and gaming literature in general, suggests that text entry may interrupt the game flow. Yet our initial user testing of the choice button and scrollbar for core gaming actions (such as training items and allocating resources) indicated that they were associated with frequent exertion of guessing and random clicking, and the lack of mindful mathematical computation. Learning system designers and educational measurement experts then argued that prompting players to enter specific numerical values would not only increase the chance of mathematical thinking but also provide more direct evidence for game-based learning assessment. This proposition was executed and infield tested. The team agreed that an intermediary interface (e.g., text entry) helped to necessitate game-based learning engagement.

***Tool*** development for the simulated design practice and mathematical problem-solving in E-Rebuild was another salient process experiencing iterative review and refinement. For example, a cutting/scaling tool that "cut/scale items along the three coordinate direction x, y, and/or z" was proposed as the following development note outlined:

> *Scale and cutting tools: Using a drag-and-highlight tool to click on the vector points of the original object (click the right area, then the area would glow to show the tolerance) to define the x, y, z value of the target cube, or to define the radius of the target sphere, or the other relative key values of the other geometry forms, to have it scaled or cut.*

This tool aims to represent various mathematical concepts dynamically. Specifically, the cutting interaction would assist the conceptual development in composing/decomposing geometric forms. The scaling interaction would assist proportional reasoning and help correct a misconception that division (multiplication) does not always create a smaller (bigger) element. Yet when prototyped and infield tested, we found that this cutting/scaling tool led to incoherent game play, due to (a) the difficulty of spawning irregular shapes/figures (e.g., cutting a pyramid or a polyhedron), (b) its conflict with the trading mechanic that aims to regulate what players can buy (since they could buy a big item and cut/scale it), and (c) the potential of breaking the thrifty rule (because scaling creates the potential to waste material). The team debated as to whether the tool should be removed. It was considered a powerful tool facilitating mathematical reasoning and learning, yet difficult to be fully executed and not aligned with the core game mechanics. The final decision was that the tool would be activated only for particular levels/tasks wherein item customization would be aligned with other gaming actions and work as a reward of successful game play to motivate purposeful geometrical reasoning.

The "highlighter" was another tool streamlined during the development phase. This tool, originally proposed to enable quick object "positioning" and integration of architectural design/planning, was built based on a concept of grid view by referring to the editing interface of Portal 2 Puzzle Maker. The following development note is a brief outline of object positioning action using a highlighter tool:

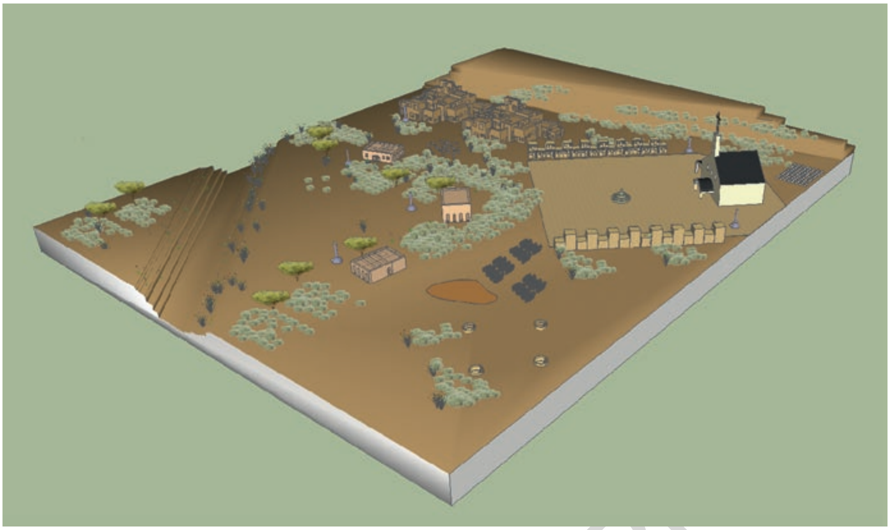
*(The player) define the construction area using highlighter tool; the defined construction area will show the grid view (with the unit of grid to be defined by the player).*
*(Click to) select the highlighted shipping container (or any constructional element/object).*
*(Click to) select the grid in which the container (constructional object) will be positioned; the object will be positioned or placed onto the grid.*
*Adjust the object's position: move, rotate, and elevate up and down (with highlighted, dotted 3D grid viewing showing).*

During prototyping, the development team found it difficult to program an active 3D grid view for the gameplay mode using Unity 3D. In addition, the introduction of a user-defined grid-view into the gameplay led to more difficult computerized gaming assessment.

***Coding game objects and developing the log structure*** are salient, interactive processes that frame the 3D game world and in-game learning/performance assessment. When coding major game objects, the team co-explored and outlined the types, key properties, and associated basic functions of game objects based on (a) an architectural building scenario script that describes and visualizes the exemplary landscape of E-Rebuild (see Fig. 3.5) and (b) the targeted mathematical concepts outlined in the aforementioned competency model. A constructional item object, for example, can be outlined in the features of forms (e.g., cuboid, cylinder, triangular prism, along with the basic functions of transforming, cutting, and scaling), physics (e.g., friction, bounciness, density, and joint strength), materials (e.g., stone, wood, brick), mass (e.g., solid or hollow), size (e.g., height, width, depth, radius, base, angle), position, and occupancy (livable or not, empty to not). The key properties and functions of each object class were then refined during the game programming phase to better align with the interface of the Unity 3D development system.

Based on the defined object classes, the game programming sub-team then drafted the game log structure that would drive the capturing of game performance and provide the gameplay data to be mined for game-based learning assessment. This log structure (see Fig. 3.6) was then reviewed and refined by the educational measurement experts in the team to ensure that the actions and states logged were in line with the task model, which was developed alongside the competency model, and to provide sufficient high-quality data for a stealth assessment of the targeted mathematical competency development.

***Assessment of game play success*** was a major execution challenge that confined the breadth of the previously defined game task evaluation and reward mechanism (see Fig. 3.4). Detecting and scoring the player's architectural artifact in the game world was challenging mainly due to the conflicting demands of creativity



AU4 **Fig. 3.5** Exemplary scenario script document for E-Rebuild. *Historic Rural Southwest Scenario*. 1 Adobe making yard with stacks of some adobes and mud pile, 2 Basic landscape and not many trees, 3 Kiva with ladder, 4 Mountains in the background, 5 Orno ovens in yards, 6 Plaza with rectilinear or square adobe houses around it, 7 Water of some kind…old-fashioned well and pumps, 8 White church with graveyard, 9 Sheep herd. *Suggested Uses of Elements for Design*. 1 Adobe bricks (pick a size and this will be a great math problem), 2 Mud for mortar, 3 Sun for drying adobes



and feasibility. For example, a fully computerized evaluation of a 3D free-form object based on the full set of architectural design and visual principles (e.g., symmetry, hierarchy, rhythm, transformation) involves developing and coding an extremely extensive (if not interminable) list of measurable/observable features in order to concretize the aesthetic representation, leading to endless programming and debugging work of the task assessment. To confine the evaluation space, clear and measurable design parameters were further delineated, prototyped, user tested, and iteratively refined. The occupancy, position, size, and shape (or form), in relation to the limits of material, time, and living needs, were settled by the team as the core design parameters for the evaluation of a built architectural structure. The sub-team of game programming and the scientific computing experts then led the discussion and the crafting of the specific formula for computing/scoring a building task (see Fig. 3.7).

**Design pattern summary** Design execution is a critical phase in which the team reviews and gauges the integration and balance of feasibility, learnability, and playability of each and every design proposition for the game mechanic, in-game learning, and assessment. Mainly via iterative prototyping in game engine, interdisciplinary expert review, and infield user testing, the team selects design features that integrate learning and play given limited time and resources and better plan the technical details that frame the interactive game world, user interactions, and the interaction performance logging and scoring.

Logging Mode switch, Tool switch, and Action switch for the later sequential analysis

| Mode | Tool | Action | Object | Time | Position | Consequence state | Potential as Math Indicator |
|---|---|---|---|---|---|---|---|
| Adventure | | Explore | | Navigation path | Subject position | | |
| | Magic wand (Green vs Yellow) | Collect | Construction elements: Container, pillar, plank, rubble, Container panel | Time of occurrence | Object position | | High |
| | | | Victims: Families in varied types | Time of occurrence | Object position | | |
| Building | Selection | Grab/Drop - Rotate | Construction elements: container, pillar, plank, Container panel | Time of occurrence | Object position; Object angle | | |
| | | Grab - Relocate | Construction elements: container, pillar, plank, Container panel | Time of occurrence | Object position | | |
| | | Grab - Stack | Construction elements: container, pillar, plank, Container panel | Time of occurrence | Object position | | |
| | Linking | Link | Construction elements: container, pillar, plank, Container panel | Time of occurrence | Objects linked | errors occuring | |
| | Earthquake test | Observe | Construction elements: container, pillar, plank | Time of occurrence and ending | n/a | Object falling or not? | |
| | Purchasing | Buy | Construction elements: container, pillar, plank | Time of occurrence | n/a | Type and quantity of objects purchased | High |
| | Measurement | Measure | Terrain, landmark object, or construction objects | Time of occurrence | Beginning and ending position being measured; Is it on an object or not? | Result saved to Scratch pad or not; Angle entered | High |
| | Cutting | Cut | Non-composite Construction elements: pillar, plank | Time of occurrence | Object being cut | The values of x, y, z entered; Tracking the states of each part of the original object??? | High |
| | Scaling | Scale | Non-composite Construction elements: pillar, plank | Time of occurrence | Object being scaled | the values of x, y, z and ratio entered | High |
| | Painter | Paint | Construction elements: container, pillar, plank | Time of occurrence | Object being painted | Color used | |
| | Historic view | Zoom in/out | Camera | Time of occurrence | | The ending state of the view | |
| | | Measure | Terrain, landmark object, or construction objects | Time of occurrence | Beginning and ending position being measured; Is it on an object or not? | Result saved to Scratch pad or not; Angle entered | High |
| Menu | | Read | Menu tabs activated/opened: Episode, Help, Inventory, Scratch Pad | Time of occurrence; Time spent | n/a | | |
| | | Click to assign/remove | Items interacted within a tab: Assignment panel | Time of occurrence; Time spent | Types of families assigned/removed | Errors occuring, Remove family with area left, Add family with area left | High |
| | | Roll over or highlight to read | Items interacted within a tab: Inventory | Time of occurrence; Time spent | Inventory items checked | | |
| | | Type to calculate or note | Items interacted within a tab: Scratch pad | Time of occurrence; Time spent | n/a | Content typed | High |
| Sub-task | | | | Time of occurrence; Time spent | | Passed - true or false, happiness score, time credit, material credit | High |
| End level | | | | Time of occurrence; Time spent | Position of the construction | Passed - true or false, happiness score, time credit, material credit | High |

**Fig. 3.6** An example of game log structure draft

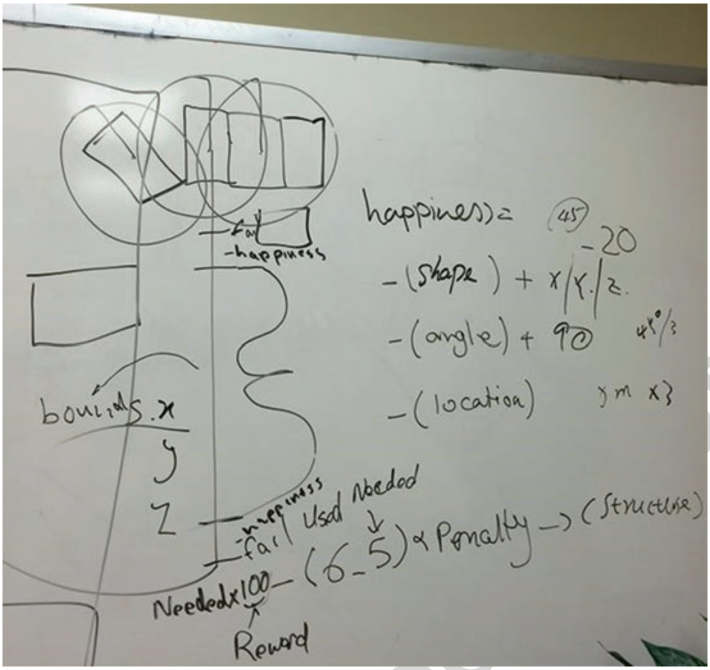



**Fig. 3.7** A white-board sketch of the scoring of an architectural artifact

### *3.2.5 Structure and Navigation of Game Levels*

**Problem statement** Designing the structure of game levels to create a responsive, game-based learning path is another critical design inquiry for the E-Rebuild team. For example, what should be the difficulty level for the initial game task/level? How should a task, level, and multilevel episode be structured? Should the navigation across the game levels be linear or nonlinear? When addressing these questions, one could resort to multiple approaches of game structuring, including the segmentation of an in-game adventure story, a gradual introduction of game mechanics, a scaffold of mathematical learning and problem-solving, and/or an accumulation of performance data to drive the training and test of an assessment model (e.g., a Bayesian network). One might also argue for learner-selected, nonlinear navigation to support learner autonomy versus a computer-controlled, sequenced navigation to guide gaming and learning skill development.

**Exploration of the design solution** The team had tried to integrate a post-quake-themed narrative, introduction of basic game rules and actions, and initiation of mathematical conceptual learning when designing the initial game level, as portrayed by the following design note:

*The protagonist is trapped in a hole and needs to get out. All that is available are some wooden blocks. The protagonist then needs to cross a river and all that is available are some branches. (Initial problem/task used to train the actions of moving, rotating, and stacking items.)*

*The protagonist comes across some victims who need a home built before a heavy rain comes in. (Second problem—for mathematical problem-solving)*

> *The victims can include four types of being, human adult, human child, animal adult, and animal child, or animal above and under a specified weight. A human adult has a standard requirement of space or cubic space (area or volume); the other three beings will require different proportions of standard (cubic) space.*
>
> *The site or the safe plane available for the home construction is limited (e.g., only 300 square feet, in certain irregular shape).*

*The protagonist comes across some victims who need a dam built before a river gets too high and floods the village (Another problem for a future level, potentially).*

*The protagonist comes across some villagers who complained about their homes or shelters as lacking light or in wrong direction toward wind, in comparison against their neighbors (so in need of transformation such as rotation, reflection, or translation); some others complained about the size of their homes, wanting them to be scaled up (other problems for future levels, potentially).*

Based on the above design note, we then developed a mock-up of the initial game level that encompassed the prototypes of the game world (e.g., earthquake simulation, blocks and containers as the building items, and victim characters), basic gaming actions (e.g., collecting and maneuvering items to build, allocating victims to the built structure), constraints/rules (e.g., time, materials, design parameters, and living space requirements), user interface (e.g., a help panel, feedback, a measurement tool), and evaluation rules of the structure built (e.g., checking whether the size/location/direction replicates the pre-quake model to 90%). Specific mathematical context problems embedded within the game levels were drafted by the mathematical education expert in the team based on a collection of state and common core test items for middle-school students. An exemplary draft/sketch of a game-based math problem along with the design notes are provided below (Figs. 3.8 and 3.9):

*Building a shelter via shipping containers to accommodate the victims saved:*
*16x10 + 8π square meters open space for potential construction, 67 people (40 children, 20 adults, 7 pets), 16 small containers (6 x 3 x3), and 8 big containers (12 x3 x3) requiring 5 meters higher than the base for living space*
*Minimum space for pet, child, and adult: 1:2:4*
*Maximum space for pet, child, and adult (meaning numbers bigger than this maximum will not influence living being's happiness any more): 2:4:8*

The mock-up was iteratively refined through user testing with a small group of middle-school students in a local school's after-school program. It then served as the initial archetype for the development of additional game levels.

**Structuring and navigation** To plan and explore the structuring and navigation of game levels, the team has referred to instructional design strategies (particularly elaboration theory, Reigeluth, 1992), prior work on flow experience in gaming (e.g., Csikszentmihályi, 1990; Kiili, 2005), and discussions of evidence accumulation across tasks in the evidence-centered design approach (Mislevy, Almond, & Lukas, 2003). A conceptual framework on how to sequence and navigate levels based on

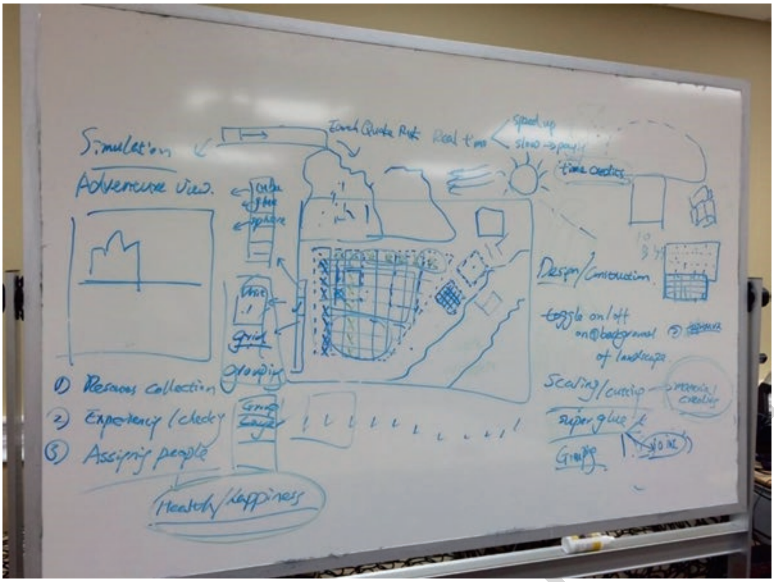



**Fig. 3.8** A design sketch of the initial game level

the embedded math competencies, the highlighted architectural design scenarios, and the difficulty index of tasks, was then drafted (see Fig. 3.10). We then proposed that the player could proceed across levels by (a) exploring tasks of the same architectural design scenario and same subset of math topics but varied difficulty levels and then advancing to a different scenario with different subsets of math topics (as portrayed by the blue line in Fig. 3.10) or (b) exploring varied architectural design scenarios along with different sets of math topics at a similar difficulty level and then advancing to more challenging tasks (as portrayed by the red line in Fig. 3.10). Path *a* or *b* can be set by the computer as a fixed, linear sequence for all players. In comparison, the game can allow the players to self-choose a path, to skip certain levels, or even to explore any levels without a sequence/path.

The team was indecisive as to which path to employ. Path *a* appeared to be more aligned with E-Rebuild level development sequence and hence was executed first in our initial infield feasibility studies with 66 6th–7th graders in their science or math classes. The infield observation indicated that players differed in their gameplay progress and naturally shared/compared their gaming experiences. While some remained stuck in Scenario 1, others had proceeded to Scenario 2 or even Scenario 3. The former group demonstrated obvious frustration when their peers showed off the new game landscapes and items. Besides, not all students managed to complete all scenarios within the study sessions and hence process all embedded mathematical concepts, which made it challenging to accumulate sufficient evidence or data across tasks for the game-based math competency/learning assessment. It also reduced the potential to provide an equivalent access to game-based mathematical


**Fig. 3.9** Computerized prototyping of the first E-Rebuild level

learning content. Given these infield findings, we then switched to Path *b* in the later infield implementation studies and found that the aforementioned issues all got resolved. Another infield finding from our design experiments with the game level structuring and navigation was that middle-school students were not adaptive to the open-ended task structure and frequently requested help with chunking and sequencing steps of the design problem-solving in a game level (Ke et al., 2017). Even though some E-Rebuild team members had argued for the sense of autonomy afforded by a nonlinear navigation with the player choice, our experimental findings,

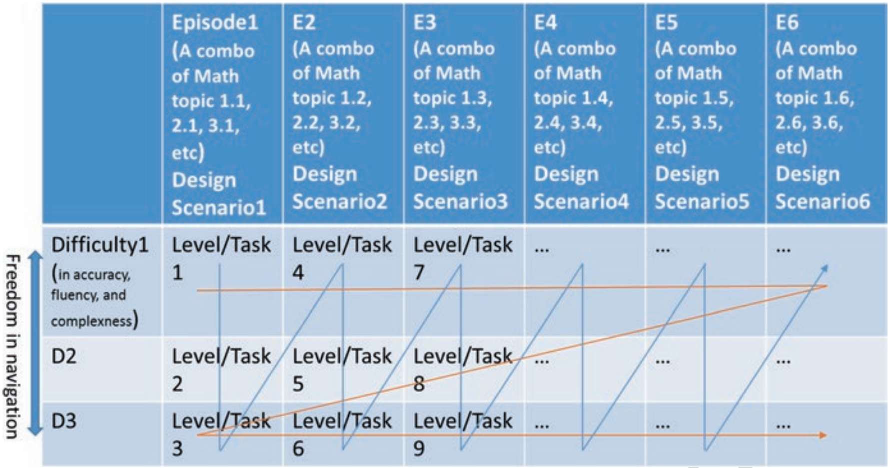



**Fig. 3.10** Game level sequencing and its integration of math competencies and design scenarios

consistent with prior research (Kim, Almond, & Shute, 2016), implied that nonlinear gameplay did not produce better game engagement or task performance but could negatively impact the evidence accumulation for game-based learning assessment. Therefore, a linear gaming structure was adopted.

**Design pattern summary** In a learning game that aims to incorporate content learning, authentic problem-solving, and stealth learning assessment without interrupting the game flow, the structure and navigation of game levels should be designed to scaffold play, learning, and assessment simultaneously. Specifically, the initial game levels should train the player on core game mechanics and frame the backdrop mission or theme narrative that embed, represent, and contextualize domain-specific concepts or problem-solving. Game structuring, encompassing the structuring of targeted competencies, scenarios, and tasks variant in difficulty, should scaffold conceptual or skill development as well as evidence accumulation for learning assessment. Game-based navigation or learning path should be selected and dynamically adjusted based on learners' response and performance during the infield testing.

## 3.3 Constructive Conflict, Group Synergy, and Leadership

Aside from the aforementioned salient design processes and patterns, constructive conflicts, group synergy, and leadership were three emerging, prominent themes found to advance segmented multidisciplinary perspectives and skills toward coherent interdisciplinary design. They developed given purposeful preparations that took some effort. These preparations involved (a) confronting and discussing issues of scope and definitions to frame a common design goal or space, (b) using a common set of design aids to identify linking points between disciplinary propositions and activate group synergy in the solution exploration, and (c) building participative and transformational leadership to reduce deconstructive conflict and create efficient decision-making.

### *3.3.1 Framing a Common Design Goal and Space*

Team members of different disciplines initially proposed interpretations of the design goal or the scope of design space for E-Rebuild, as implied by the following meeting note that recorded team members' perspectives on the most unique feature of E-Rebuild.

- *Mini-me (embodied* via *a 1.5 meter middle-school student figure) performing various architectural design/building activities.*
- *Integrating math history into the gameplay, for example:*

  *An AI agent (history agent) has time-traveling power and can present not only the views of the site/architectures before an earthquake but also the history of ancient construction tools (e.g., perpendicular lines in the coordinate plane) or practices (e.g., proportion reasoning when measurement units are not standardized or existing).*

- *3D object maneuvering and transformation*
- *Development and validation of game-based stealth assessment of learning.*

The above perspectives were presented by the scholars from the disciplines of architecture, mathematics education, scientific computing, and educational measurement, respectively. Such a diverse range of design priority propositions were found to expand the scope and create a segmented agenda when framing the design space. Thus, our initial design meetings mainly focused on consolidating design goal interpretations.

Moreover, an interdisciplinary design team has different customs of classifying or naming design concepts, which made the design discussion and brainstorming at the initial design meetings especially challenging. For example, scholars of learning systems design, architecture, and scientific computing all had variant usages for terms. Some examples include "blueprint" versus "floor plan" or "site plan," "God's view" versus "plan view" or "elevation view," and game "level, episode, or chapter," which led to an initial discussion on the design of gaming perspective and the game world projection confusing and clumsy. Documents explicitly defining architectural vocabulary, disciplinary concepts, and gamer terms were hence drafted to assist interdisciplinary design communication, as the following example illustrates (Table 3.1).

**Table 3.1** An exemplary sketch specifying gaming and scientific computing vocabulary

| Building items (gaming) | Objects (scientific computing/coding) |
|---|---|
| Forms | Forms: cuboid, cylinder, sphere, triangular prism, cone, pyramid<br>Transformation, cutting, scaling |
| Materials (e.g., stone, wood, brick, and steel, glass?) | Physics: friction, bounciness, density, joint strength |
| Solid/hollow | Mass (Can hollow objects be cut? Center of mass?) |
| Size | Height, width, depth, radius, base, angle |
| | Positioning |
| Livable space | Occupancy |

### *3.3.2 Using Common Design Aids*

Exemplary design cases in architectural and learning games were used as the "seeds" or the design aids to help the team identify linking points between disciplinary propositions and activate group synergy in the solution exploration. The following project meeting note highlighted the usage of design examples as the starting point for the team to identify the linking points between disciplinary propositions and activate group synergy in the solution exploration:

*9/28*
*We have decided that before next meeting, we will further explore gaming tasks and core mechanics of E-Rebuild by reviewing the Bridge! Construction game, Minecraft, and Google SketchUp. The following is a suggested list of design questions to be considered/addressed during the review.*

*What are the major game mechanics? Is it given resources and design constraints, build or compose architecture?*
*What is the potential of mixing survival mode (speeded construction task) and creative mode (simulation mode in which one can test the construction product with the earthquake tool)?*
*Game actions: Moving, stacking, cutting, and scaling? Model sketching within the game?*
*Rule: Limit of constructional items as a constraint of design? Reward the level pass with more inventory items?*
*Will a building block (e.g., a cube or shipping container) be given by the system? How and why should the system give the player with shipping containers? Any story element?*
*What game rewarding system?*
*How will the tools be given to players, one at each game level, or once for all at beginning?*
*How will players learn to play?*

*We have decided that each teammate should present a design sketch or a written document to address the above questions and then have all thoughts synthesized during next meeting.*

### 3.3.3 Building Participative and Transformational Leadership

As the above design note illustrates, the team of E-Rebuild resorted to participative design practice that values the input of every team member and holds everyone responsible for design brainstorming. A prerequisite of such a design style was the lengthy discussion and congregation of each and every perspective in the project meetings, extending the duration of the group meeting. Frequently, a common synthesis could not be reached, and the meaningful negotiation was abruptly stopped when a meeting adjourned. To increase the efficiency of decision-making and ensure the design discussion would be thorough, we divided the whole team into groups based on major design responsibilities, with each group led by a disciplinary expert. We also separated the design meetings into two sections, the whole-project meeting and the sub-team design meeting. At the former ones, we focused on the big picture, sharing the reports of every sub-team and conducting high levels of communication/decision-making to accomplish design goals. Smaller and detail tasks were delegated to each sub-team who would hold separate sub-team design meetings to fully discuss and explore the solutions to discipline-specific design inquiries. These solutions would be brought back to the whole-project meetings for review and critique. In general, we observed that such a mixture of participative and transformational leadership (Burns, 1998) aided in efficient and constructive design decision-making in an interdisciplinary team.

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# Author Queries

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| Queries | Details Required | Author's Response |
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| AU1 | Please confirm the identified head levels are okay. | |
| AU2 | Please confirm the inserted citation for Figs. 3.1 and 3.4. | |
| AU3 | Please provide better quality artwork for Figs. 3.1, 3.3, and 3.5. | |
| AU4 | Please confirm the caption for the Fig. 3.5. | |
| AU5 | Please provide publisher location for Moustakas (1994). | |

# Chapter 4
# Design of Gameplay for Learning

**Abstract** A common skepticism about educational games is that learning and play are frequently not well integrated—the skill or content to be used and learned lacks a semantic or meaningful relation with the fantasy and challenge elements and can be easily swapped without influencing gameplay. In this chapter, we describe and analyze design challenges associated with the core components of gameplay—game mechanics and the narrative scheme for the learning purpose—and review the gameplay design propositions and infield test findings of E-Rebuild. Via a retrospective investigation of design features and strategies in terms of learnability and playability (i.e., capability of activating knowledge-based cognitive performance without interrupting gameplay), this chapter aims to report and discuss how domain-specific learning is integrated in and activated by core game actions, rules, game objects, and the game world design.



## 4.1 Introduction

AU1 Gaming is an organized play structured by a set of rules and an obstacle-tackling goal (Klopfer, Osterweil, & Salen, 2009; Schell, 2014; Suits, 1978). Learning is an innate element of gaming, in that players interact with a game to learn rules and play strategies and then adapt and improve play skills to make progress in the game (Lindley & Sennersten, 2008). Yet learning in games varies in the degree to which the acquired skills and strategies emphasize "domain-specific knowledge" (Ke, 2016; Tricot & Sweller, 2014). The higher-degree domain-specific knowledge is needed, the more careful design effort is required for the attainment of an integral relationship between gaming and learning (Habgood & Ainsworth, 2011; Kafai, 1995; Malone & Lepper, 1987; Torbeyns, Lehtinen, & Elen, 2015). A common skepticism about educational games (and, hence, a relevant design issue) is that learning and play are frequently not well integrated—the skill or content to be used and learned lacks a semantic or meaningful relation with the fantasy and challenge elements and can be easily swapped without influencing gameplay. As a result, players may be distracted by the play part and not achieve the learning goals, or they



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may become disengaged because learning elements may corrupt what is enjoyable about games (Garris, Ahlers, & Driskell, 2002; Miller, Lehman, & Koedinger, 1999). For example, in E-Rebuild we could design a “trading” challenge that requires the player to complete a screen of math questions to obtain the corresponding number of game tokens and then use the tokens earned to purchase items needed. Such a game mechanics (i.e., the question-answering point system) could be reused for another challenge (e.g., earning time credits to buy more time for a “building” action) only with the content or math topics of the questions swapped as needed. An extrinsic integration of content in gameplay, as the example illustrates, appears to be a rapid and all-purpose gameplay design strategy. But it is, as prior research suggested, deficient in reinforcing game-based engagement and won’t likely promote desirable active and deep learning, especially for learners who lack the competency of and positive disposition toward the subject matter (Ke, Xie, & Xie, 2016; Richards, Stebbins, & Moellering, 2013).

In this chapter, we describe and analyze design challenges associated with the core components of gameplay—game mechanics and the narrative scheme for the learning purpose—and review the gameplay design propositions and infield test findings of E-Rebuild. Via a retrospective investigation of design features and strategies in terms of learnability and playability (i.e., capability of activating knowledge-based cognitive performance without interrupting gameplay), this chapter aims to report and discuss *how* domain-specific learning is integrated in and activated by core game actions, rules, game objects, and the game world design.

## 4.2 Conceptualization of Game Mechanics, Narrative, and Learning Integration

Endorsing the perspectives of the previous game studies, we have designed and examined the construct of gameplay in two layers: the “ludus” or game mechanics layer that involves rules and actions and the narrative layer that comprises the setting (or scenario), backdrop mission, and game objects (Ang, 2006; Frasca, 1999). It is commonly believed that gameplay lies in the meaningful interplay between the two layers, though whether game design is more the design of experience (Salen & Zimmerman, 2004) or a narrative architecture (Jenkins, 2002) is still inconclusive.

According to Järvinen (2008) and Sicart (2008), the term game mechanics refers to an activity structure consisting of rules and play actions. Rules are designed to determine the conduct and standard for both play behaviors and the winning/losing state. These rules lead to the creation of player strategies and actions with which the player can interact with game elements to “influence the game state towards the attainment of a goal” (Järvinen, 2008, p. 255). The game mechanics hence is “a compound activity composed of a suite of actions” that players, abiding by the rules, recurrently perform and directly apply to achieve the goal state (Salen & Zimmerman, 2004, p. 316; Sicart, 2008).

Not all games tell a story, and hence the narrative layer is not a defining feature of games (Ke, 2016). But many games do have narrative aspirations, or at least tap into the player's memory of previous narrative experiences (Jenkins, 2002). According to Jenkins (2002), narrative can be integrated into a game as a broadly defined goal, such as a backdrop plot or mission, (b) a localized incident or plot developed in game level(s), and/or (c) an open-ended game world that allows players to define their own stories via authoring- or construction-based play. Notably, a game can create an immersive narrative experience and convey storytelling via the "spatiality" of the game world, in which the narrative element is infused into a space that a player navigates through and interacts with. In E-Rebuild, we have explored the aforementioned three approaches of the narrative layer during the design process and in particular focused on examining the feasibility and effectiveness of representing a mathematical story problem via the spatial narrative of the game world.

In a recent literature review of domain-specific content learning via gameplay (Ke, 2016), the typical processes of integrating learning in game actions are described as representation, simulation, and contextualization. Specifically, *representation* involves designing game objects as external representations of the targeted concepts and interactions with game objects as the conceptual exploration or application processes. *Simulation* is achieved via designing the game world as a scientific problem or system and hence the game actions as an iterative process of problem-solving and discovery learning. *Contextualization*, conveyed via a backdrop mission, a plot, game characters, and/or meaningful scenarios, is then employed to increase the pertinence and fascination of content representation and problem-solving simulation for players.

## 4.3 Learning-Play Integration in E-Rebuild

The design of E-Rebuild has been inspired by previous sandbox or architecture game examples (e.g., Minecraft, SimCity), 3D modeling tools (e.g., Google SketchUp), and the previous architectural design education programs for children (e.g., *Architecture and Children Pilot Curriculum*; Taylor, 2009). Different from and extending these design stimuli, E-Rebuild needs to align and combine construction-/authoring-themed gameplay, accessible 3D design, and interaction interface, as well as architectural design missions and setting, to facilitate mathematical learning and problem-solving for middle-school students. Designing core game mechanics that manage to embody such an interdisciplinary design goal is critical and challenging. What should be the nature or foundational "act" of the interdisciplinary, learning-constructive gameplay? What corresponding game actions and rules are found to reinforce the game's learnability and playability? How will backdrop and virtual narrative environment contextualize or "legitimize" the target learning and play actions?

The aforementioned questions underlay our design inquiry on the core game mechanics of E-Rebuild. We conducted a retrospective and thematic analysis with the design notes, meeting records, design talk among teammates at meetings, and the observation notes of players' actions and reactions when test-playing the prototyped E-Rebuild game levels. The analyses focused on delineating salient design propositions and beliefs governing the core game mechanics and narrative scheme, refined perceptions and design moves during infield testing, and the identified, functional design heuristics that promote in-game learning actions without interrupting the flow of play. These design research findings, with support of citations and examples, are presented below in a succession of themes that collectively constitute the thinking process and core sectors of the game mechanics and narrative design process.

### *4.3.1 Setting Genre and Nature of the Core Gameplay*

There were two intertwining threads of design effort in the initial inquiry of core gameplay design in E-Rebuild—searching *the genre of building-themed gameplay* and investigating the nature of *building-relevant mathematical experience*. The former thread of design effort highlighted the element of play by addressing the following questions: "What will be building-themed play? What is the core action of play? What will be the major obstacle and goal for such a play act?" The latter thread of design, differently, focused on the learning experience by defining the core components of a salient or desirable mathematical experience or thinking process. The intent was to seek the salient and unified actions existing between architectural design and mathematical knowledge application and gauge how and why these interdisciplinary actions could be challenging while personally meaningful for student players to be "fun."

**Genre or type of building-themed gameplay** *Why is building fun*? was the headline title of the first design meeting memo of the E-Rebuild project, exemplifying the predominant and early design effort contributed to exploring the potential genres of serious play enabled by the processes of planning, designing, and constructing buildings and other physical structures. Such an exploration was activated via (a) an inspection of toys, games, simulations, and other hypermedia examples highlighting the theme of building, especially survival rebuilding activities, and (b) a reflective design conversation among the design team members in relation to our own experiences and preferences of building-themed gameplay.

The design team members of E-Rebuild have, individually and collectively, sought, reviewed, and test-played a collection of architectural construction- or building-oriented toys, games, simulations, and other hypermedia applications. The assorted prior examples of building-themed serious play demonstrated various modes of play, such as block stacking puzzle (e.g., https://play.google.com/store/apps/details?id=com.ketchapp.stack), block building in the real or virtual world (e.g., Magna-Tiles, Minecraft), adventure (e.g., Raw Danger!, Camelot Unchained), strategy game (e.g., http://www.stopdisastersgame.org/en/home.html), and physics simulation (e.g., Bridge Constructor, Bridge Construction Simulator). These examples of building-themed gameplay could evolve around a designer-defined *game goal* or the preset criteria for game success, such as height and balance in block stacking, sturdiness of the construction, survival, and/or people and property protection against a disaster. It may also depict an open-ended, self-determined goal of play, such as creative play via block building in a sandbox game. Core *player or user actions* include block stacking (information or object) collection, and decision-making, with *real-time physics* simulation activated, elective, or deactivated during those actions. Reflecting a focus on an adventure or a construction mode of play, the core gaming action will adopt *a plan view or an elevation view*, whether in first- or third-person perspective. Ultimately, the *obstacles* to be resolved to achieve the play success are typically the challenge posed by the properties of the building materials in relation to the construction goal (e.g., the weight, shape, structure, variety, and/or scarcity of construction materials in a block stacking puzzle or a bridge construction game), time limitation, and insufficiency of prerequisite knowledge or skills of a construction task (e.g., engineering concepts in Minecraft; physics in Bridge Constructor; science, economics, and global issues in Stop Disasters; or generic problem-solving skill in Raw Danger!).

The design case review and test-play notes of the design team indicated variability among the team members in terms of the play preference, discipline knowledge, and hence the thought processes for design. For example, regarding two exemplary construction- or building-themed games, a game designer commented, "I think what we can learn from these two games, are the game actions and the potential design constraints we can have: Given a landscape or terrain, given the potential risk of future hazards and limited budget and materials, where and what kind of post-quake architectures should we invest on and build?" The comment carried the game design language (e.g., "game actions" and "constraints") and a designer perspective governing the common core game mechanics in the game examples. Yet two team members, a mathematician and an educational measurement specialist, made different annotations (provided below). These annotations highlighted the player perception, indicating different player preferences.

> https://eduweb.com/portfolio/bridgetoclassroom/engineeringfull.html
> http://www.stopdisastersgame.org/en/home.html
> Cool games. I just looked them over quickly, and they seem interesting!
> I played the bridge game and it was boring. The other earthquake game was a bit more engaging, but not by much. We have a chance to build a more compelling game for this niche!

The second commenter then expressed her preference of adventure games (e.g., *Raw Danger!*) that got concurred by another team member who was also a fan of sandbox games like *Minecraft*.

Indeed, *play preferences* tended to mediate how individual team members framed the role of building or constructing in the play experience. Some perceived the task of construction or building by itself as a fun process, thus framing the core gameplay as the simulation of building actions and replicating architectural design constraints and specification as the obstacles and goal state. Others considered building mainly a backdrop mission or a meaningful context that legitimizes the gameplay of creative problem-solving and adventure. Another individual characteristic that mediated the thought processes for building-themed gameplay design is *disciplinary knowledge* or *epistemology*. The architecture educator, for example, insistently emphasized the basic principles of design (e.g., balance in visual distribution, rhythm, unity) and creativity as core goal states or success evaluation criteria. Yet game designers and programmers in the team preferred measurable objectives (e.g., time, thriftiness in material usage, structural soundness, and building specifications of a structure) and expressed concern as to whether and how some principles and elements of design can be defined and specified quantitatively for computerized in-game evaluation. Certain team members also worried that giving players unlimited materials and seeing what they create would eliminate constraints, thus reducing the challenge and hence fun in the game.

After multiple rounds of reflective and active conversations with the design cases and teammates on the type of building-themed gameplay, we decided that our prototype of the core game mechanics would try to integrate different design perspectives, which would be infield tested by the learners and then refined based on the testing data and learners' feedback. Our initial prototype of building-themed gameplay, therefore, encompassed the following elements: (a) shifting between a first-person, adventure mode (with collection, site measurement, and space allocation as sector-specific game actions) and a third-person, building mode (with trading and building as core game actions, Fig. 4.1); (b) simulating physics (e.g., earthquake waves) to test the structural soundness of a building artifact; (c) enabling both plan and elevation view in the building mode (Fig. 4.2); (d) depicting building obstacles as the variety of landscapes, time, and material limit; (e) defining/evaluating the goal stated mainly via time, materials usage, structural soundness (e.g., not collapsing given variant earthquake waves), and preset building specifications (e.g., size, location, and direction aligned with a pre-quake house model); and (f) letting peers and potentially the teacher rate the aesthetic design elements and originality of the structure outside the game during post-game debriefing. This prototype later got iteratively reviewed, user tested, and refined considerably, as described in a later section.



**Building-relevant mathematical experience** Another concurrent thread of design inquiry on core gameplay in E-Rebuild was to investigate the salient, common features of both a mathematical experience and an architectural design/construction experience, or *What makes a good building task or activity that creates engaging and effective mathematical experiences for participants*? Exploring building-relevant mathematical experience is critical for an intrinsic integration of learning and building in gameplay. The exploration process evolved around the interviewing of disciplinary experts, the literature and design case review, and an inspection of exemplary design education curricula (e.g., *Architecture and Children Pilot Curriculum;* Taylor, 2009) that promote the dynamic architectural and mathematical experiences for children.


**Fig. 4.1** Adventure and building modes of play

The design discussions on the joint features of architectural and mathematical experiences involved the analysis of core actions, basic resources or materials, frequently used tools, requisite knowledge and skills, and a set of archetypal practices typifying the aforementioned elements. For instance, the following game design note carried initial discussions on the potential conjoint architecture-math experience elements.

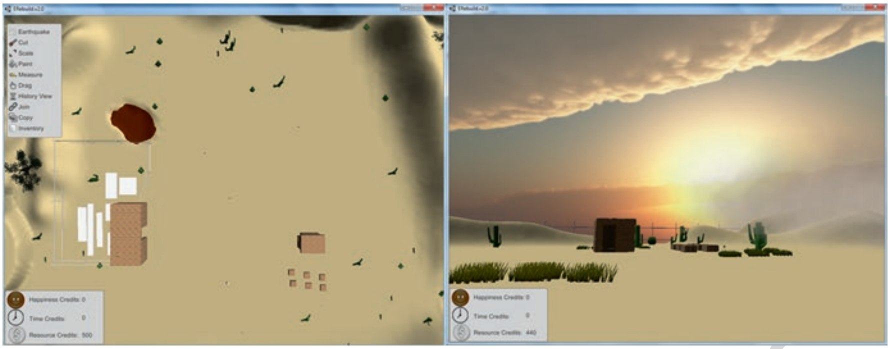

**Fig. 4.2** Plan and elevation views

*Tools*

- *Measuring/layout tools: rule, square, protractor,* etc.
- *Sketching tools: brush.*
- *Construction tools:* e.g., *cutting, transportation, elevation tools,* etc.

*Basic materials*

- *Building unit: line, plane, form, or prefabricated block.*
- *Shape: cube, arch, cylinder,* etc.
- *Texture: stone, brick,* etc.

*Actions*

- *Navigate and explore (*i.e., *measure, collect data, and analyze data).*
- *Draw or sketch* via *extended devices and apps—mixed reality.*
- *Build: select, drag, drop, and customize.*
- *Test (*e.g., *with simulated earthquake waves) and predict, decide, or reflect.*
- *Collect, trade, and/or manage resources (*e.g., *time, space, material cost).*

*Exemplary Practices*

- *Develop architectural plans and a model for a "mouse" house: Bubble diagram –> floor plan (a plan view) –> elevation drawing (2D drawings that show the outside walls of a building,* e.g., *the front side with door) –> perspective drawing (a house that is three-dimensional looking) –> model construction.*

- *Related task (p. 8 in* Taylor, 2009*): Designing a vegetarian fast-food restaurant (eating and preparation areas, delivery space storage, restrooms, parking,* etc.*—spaces only, not equipment).*

- *Predesign exercise or puzzle: decorate a shoe*
- *Structure in architecture: arch, triangle, or asymmetrical* vs. *balanced.*
- *Related task: The picnic shelters must use a space frame structure for their roofs. Each shelter will have four picnic tables, and the space frame will rest on at least four columns.*

- *Predesign exercise or puzzle: Toothpick puzzles*
- *Form in architecture, involving measurement, data interpretation, scale, and proportion.*
- *Related task: Use organic structures found in nature in a "fantasy" architectural structure for the "moon."*
- *Predesign exercise or puzzle: Scavenger hunt for basic geometric shapes and forms in nature (*e.g.*, crystal, plants' spirals, spider's net) (p. 31).*
- *Related task: Design a "people's" bridge across the canyon to build a jogging and bike path. This bridge should be as beautiful as the landscape that surrounds it and should appear to gracefully and sturdily cross the canyon (p. 35).*
- *Predesign puzzle: Designing and modeling natural bridges—a fallen tree as a beam bridge, intertwining vines as suspension chains or bridge, and a rockfall and later the water eroded some rocks away forming a simple arch over the stream (*i.e.*, the arch bridge) (p. 33)*
- *Visual design: Super wall graphics using concrete block or block grid pattern enlargement method (scale, proportion, measurement, introduction of area and perimeter) (p. 38).*
- *Related task: Drawing and painting a supergraphics for your village's school, which will represent your community.*
- *Predesign exercise or puzzle: Painting an existing graphic projected onto a brick wall. Mixing color and texture*
- *Creative, imaginative design: My favorite place.*
- *Related task: Design and model an "ideal classroom" using a scale, and then construct it.*
- *Similarities between body and building systems (membrane-skin, mechanical systems-muscular system, heating/cooling-circulatory system, electrical system-nervous system, structural system-skeleton, waste disposal system-digestive system, ventilation-respiratory system, mechanical devices that lift and push things-muscular system).*
- *Related task: Transformer "You are architecture."*
- *Landscape (p. 45)—collaboratively make a section drawing from a topographic map of a site, schematic drawing of individual designs, and create models and the final working architecture.*
- *Related task: Redesign a creative play park for the surrounding community and the school.*
- *City planning—collaboratively plan, model, and build transportation, residential areas, business district, recreation and open spaces, and the capitol complex (p. 50) (data collection and interpretation, in addition to all prior knowledge).*
- *Predesign exercise or puzzle: mapping and touring.*

As illustrated in the above design notes, our initial exploration of building-relevant mathematical experience has pinpointed a short list of core actions—site analysis (surveying), sketching, building (design) experimentation, and resource management. Yet there is still much ambiguity and disagreement existing in the team discussions: Will the experience or actions highlight design/sketching (e.g., drawing and visual pattern design) or building/modeling (e.g., the composition and decomposition of the forms and shapes) or both? What should be the granularity level of the building action? What are the various forms the building units can assume? What and how will the tools be integrated into the game setting?

The design discussion on the role of design/sketching versus building/modeling in the gameplay experience was actually a comparative analysis on the two prospective game mechanics in enabling and legitimizing targeted mathematical practices. In particular, we discussed whether and via what enabling acts or moves the two mechanics would embody the multimodal conceptualization and application of the targeted math knowledge (e.g., angle measure, area, and volume of geometric figures). Via expert interviews and exemplary task performance observation along with task analyses, we found that the game mechanics of building or modeling tends to optimally align with the targeted learning actions (Table 4.1). We then wondered about the applicable user input interface for each action and the feasibility of in-game tracking and assessing of design or building moves. Design, especially sketching, as the game mechanics would entail high-precision touch screen interaction (e.g., tablets or laptops with stylus); the complexity involved in architectural drawing and creative design also composed challenges to real-time, in-game behavior tracking and design artifact evaluation. As such, gameplay in E-Rebuild portrayed more building/modeling actions than design/sketching actions.

The granularity level in the basic unit to be maneuvered during the building/modeling actions would vary. Specifically, using a “block” approach, the game could provide prepackaged structures (e.g., a shipping container to be remodeled as a house) as building blocks to be composed, decomposed, or modified to create variant structures. Alternatively, a player would build using the basic architectural forms (e.g., bricks, doors, windows) to compose higher-level elements (e.g., walls, floors, and roofs), then a house or bridge, then a neighborhood, and so forth. During design discussions, the team perceived that both approaches have advantages. The design hypotheses were that the previous approach would enable a novice player to construct a complicated structure efficiently while focusing his effort on planning before building. The latter, though demanding a higher level of design knowledge

**Table 4.1** Actions of learning and building

| Learning actions | Building actions |
|---|---|
| Identification and representation (e.g., of 2D/3D geometric figures) | Collection and trading (of construction elements) |
| Measurement and calculation (e.g., of length, angle, circumference, area, and volume) | Construction site survey and plan |
| Creation | Building—positioning, rotating, stacking, joining, copy-pasting |
| Analysis | Allocation of space, time, and other limited resources |
| Evaluation | Design evaluation: fulfilling needs, efficiency in cost and time |

and technical fluency, would situate building units in a variety of forms in line with the system of geometric shapes to be learned. Hence both approaches were used and integrated across game episodes and tasks in E-Rebuild.

To implement building-relevant gameplay, the user input interface is another critical design element. The interface should enable core game-based learning actions while keeping players in control. In other words, it should facilitate action-based mathematical conceptualization or knowledge application beyond affording simplicity and efficiency. To explore appropriate user input interfaces for core game actions, we designed multiple papers, toys, and computerized prototypes, iteratively tested them with expert and novice gameplayers, and evaluated the interaction experiences to select the interface and interaction tools that are not only user-friendly but also learning constructive. Detailed discussions of the user input interface or tool design are provided in a later section.

### *4.3.2 Designing Learning-Play Integration in Game Actions and Rules*

During the past 4 project years, we have iteratively designed, tested, and refined more than 30 prototypes of E-Rebuild. Learnability and playability are two key objectives driving the iterative design tests and refinements. During iterative testing, we have observed a continuum of gameplay engagement framed by the designed game actions and rules—from play engagement (i.e., game-based play irrelevant to the designed tasks), task engagement, and cognitive engagement to content engagement, being incremental in demonstrating commitment to mathematical thinking, knowledge application, and problem-solving. After iterative refinement and elimination, the resulting game actions and rules have the following core feature or functionality: *necessitating cognitive and content engagement within gameplay actions* and *rewarding mathematical thinking as the most warranted gameplay strategy*.

**Cognitive and content engagement in game actions** As discussed above, the design conjecture of gameplay in E-Rebuild was that players would purposefully engage in architectural building types of game actions, solve problems framed by each game action using strategy and knowledge, and consequently experience a variety of action-based mathematical thinking processes. These thinking processes, corresponding with game actions (see Table 4.1), can involve analyzing the underlying numerical, logical, and structural essentials of each problem, representing and applying conceptual knowledge to the problem, and then engaging in reasoning and finally proof. As such, the gameplayer would develop the targeted knowledge and skills to perform mathematical problem-solving or engage in mathematical thinking. Game actions in E-Rebuild essentially necessitate both cognitive and content engagement. Cognitive engagement in the game-based setting refers to engaging in generic cognitive endeavors and making cognitive investment in tasks with purposiveness and strategy use (Ge & Ifenthaler, 2017; Ke et al., 2016). Content engagement refers to engagement in which players also establish positive value systems and get motivated in mathematical content (i.e., concepts, relations, formulas, and theorems) processing, representation, and application (Ke et al., 2016).

The user-testing findings with our initial prototypes of E-Rebuild game actions, however, indicated that many players by default lacked a disposition of looking at an architectural building or design problem in a mathematical way, or looking for a logical explanation, which is a key prerequisite of mathematical thinking. Instead, they could seek task-irrelevant gameplay, such as exploring the game world without purposiveness or creating their own play experiences with the game objects (e.g., using the measurement/marking tool to sketch on the ground rather than surveying the construction site and imagining the construction site as an arena and maneuvering 3D building materials as armaments or vehicles). They might tackle game actions and the associated problems in a mindless way, such as guessing with trial and error. They would avoid math-relevant planning or strategic thinking, lacking the acts of pre-estimating the construction cost during a trading action or predetermining the structural properties of a construction in a building action. They would also shy away from calculating the exact amount of resources available and needed during an allocation action while resorting to testing and refining rough estimates, randomly or with a content-generic strategy. They spent limited time reflecting on or reasoning with the basis and consequence of major gameplay inputs or the connection between them, thus lacking the practice of inductive or deductive reasoning. More critically, we observed that student players generally lacked initiative in reading during gaming, showing reluctance to peruse the mathematical problem or content information in a task narrative or the in-game help panel.

In summary, we found that cognitive and content engagement by players are not promised even when the core game actions embody or operationalize the salient elements of architectural and mathematical problem-solving. An earlier user-testing study indicated that the percentage of cognitive engagement of players in all gameplay actions was 41% and that of content engagement was only 29%. To improve the efficacy of E-Rebuild game actions in requiring cognitive and especially content engagement, we experimented with the following design strategies for both gameplay actions and rules: (a) prioritizing "cognitively active" gameplay inputs and behaviors that extrapolate the deed of representing or employing mathematical knowledge and skills and curtail the chance of guessing and other mindless strategies; (b) rewarding mathematical thinking (planning, calculation, and reasoning), or domain-specific gameplay, as the most *justified* gameplay strategy by players; and (c) presenting in-game mathematical information via visuals, action feedback, or properties of interactive game objects, besides background narratives.

*Prioritizing "cognitively active" gameplay inputs and conducts* that extrapolate the deed of "doing" mathematics and curtail the chance of guessing or other mindless strategies is a major design strategy. An underlying index for our selection and refinement of a core game action is whether and to what extent the action will necessitate cognitively active gameplay inputs. Specifically, we have prioritized the "producing" type of gameplay input (such as generating or constructing a numeric or quantitatively accurate solution) to "choice-making" type of input (e.g., inspecting a given set of options to choose a solution). We found the latter expedited and increased the usage of trial-and-error strategy by players. We also tried to prioritize the game action of which the associated challenge (or problem) requires the actual deed of exploiting the *resources* of mathematical knowledge and skills, rather than just *heuristics strategies* or *general reasoning abilities,* during problem-solving (Schoenfeld, 1985; Stacey, 2006). These design decisions are inferences extrapolated from the iterative infield testing of game action archetypes, as the following example shows.

The learning objective of the game action of "collection," for example, is to enable the action of identifying and representing the numerical and structural properties of everyday objects and phenomena (e.g., shapes and measurements of construction materials, structure of a family with the ratio of adult to child in their minimum living space needs). Our original design assumption was that players would proactively perform a variety of relevant learning acts (as depicted by an initial design note below) enabled by and during the collection action, with the provision of a measurement tool, a goal statement for the collection action (e.g., using containers to construct a shelter), and visual/verbal cues (e.g., a family cartoon signifying the composition of family member, a mathematical statement on the unit space need).

> Exploration, including measuring and appraising the landscape, is part of material gathering. We could integrate site analysis and terrain judging (e.g., on what part of the site is higher or has solid ground for building?).
> Decision-making: What and how much materials to gather, given design needs and the limited time and capability (limited storage space or limited tool resource). How can we softly push a player to perform accurate calculations when gathering materials in the game?
> Transformation: If the geometry forms or elements exist somewhere, simply gathering them is a lucky act. The problem is that if one needs to use a complicated component, he or she will need to comprehend and use the complex geometry or geometry transformation. How can one decompose and recompose diverse geometry components?

The infield observation, however, indicated that most players treated the collection action literally as the "treasure hunting" gameplay. They focused on searching for objects dispersed in the game world, with few purposefully identifying, checking, or measuring the dimensions and other structural properties of the objects collected. They did not fully process the goal statement or attend to the cues on the structural or numerical properties of game objects, demonstrating the intention to treat this information as trivial to their "at-hand" game objective—gathering all objects to be gathered.

These observations suggested (a) a misalignment between the action-specific learning and game objectives in that the instant or by-default solution to the action-specific challenge is learning-irrelevant (e.g., navigating the game world to obtain objects), (b) participants' lack of motivation to tackle a game action and challenge via a mathematical strategy, and (c) participants' lack of a planning perspective to anticipate the relation between individual pieces of information or individual moves to an overall plan and hence short of identifying and analyzing the mathematical properties of individual objects (e.g., a shipping container or a family) to fulfill future game actions and objectives (e.g., allocating the limited space afforded by a certain number of containers to a set of families). The consequential design insight is that our target middle-school students typically lack attitudes, behaviors, or skills expected to perform purposeful, cognitively effortful, and mathematical gameplay. Motivating participants' purposiveness and proactivity in cognitive and content engagement is important for the game action design.

To foster the cognitive and content engagement associated with the collection action, we tried prioritizing the investigation of the numerical and structural essentials of each item to be collected, rather than item-hunting in the virtual world, as the primary action-specific challenge. For example, the player had to measure and compute the living area of a shipping container and the living space need of a family before the container and the family can be gathered. We tried adding the "producing" type of user input that requires the actual deed of exploiting the *resources* of mathematical knowledge and skills, such as prompting the player to accurately compute and inscribe the numerical values of the numerical and structural properties of the collected items. We also experimented with the strategies of externalizing, chunking, and presenting the sub-goals of the multistep game task, in an attempt to cue the player on the integration of the at-hand moves and individual information pieces to the future game actions and objectives. These design strategies have evidently improved the players' time spent on and the frequency of enactments of mathematical information processing and reasoning processes, as evidenced by both the game-logged task performance and gaming behavior analysis (Ke et al., 2017).

*Rewarding domain-specific gameplay (i.e., mathematical planning, calculation, and reasoning) as the most effective gameplay strategy for players* is critical for motivating game-based mathematical practice. As the literature of game-based learning (Hamlen, 2012) discussed and we observed in our own design experiments, the goals and values of individual uses are not necessarily allied with the designers' expectations or conjectures. A hypothesis of learning games is that gameplay should be both result and process driven—achieving game objectives and the processes of problem-solving to achieve the objectives are both important and enjoyable. Yet students frequently prioritize the result state (e.g., "passing this level") to different challenges, sometimes to an extent that they would try to bypass difficult tasks instead of working through them, adopt certain "cheating" strategies, or give up when a task was difficult. Fostering a positive disposition and the grit to tackle a game challenge via a mathematical strategy is therefore a critical goal and condition of game-based learning. In the following subsection, we describe three salient themes that emerged from our design research and governing game action-specific constraints and rewards that helped to motivate E-Rebuild participants' attitudes and behavior change in terms of mathematical thinking and practices.

*From fluky psychology to mathematical reasoning* During interviewing, we found that participants' pre-study gaming experiences appeared to foster a *fluky psychology* or belief in randomness during game-based problem-solving. An exemplary participant quote is, "This (E-Rebuild) is different from Minecraft. (In) Minecraft you do whatever you want. This is picky." Fluky psychology was observed in the following gaming behaviors:

> (In a "trading" game action) Bob[1] repeated the same guessing and trial-and-error strategies as before. He read the task description in less than 5 seconds and did not attend to the item price bulletin inside the store. He entered random numbers (for the bid of a construction item) into the ordering area, executing a trial-and-error strategy. He tried five times and realized that it was not an easy guess after repetitive failures, before finally returning to the virtual store to read (process) the price bulletin.
>
> Bryan continued the similar trial-and-error play with the trading action. His neighbor commented, "This is Bryan! You don't care." Bryan laughed and started to refine his play strategy. In the ordering area, he placed 10 as the number of bricks to be ordered, thought for a minute, and then put 45 as the total cost (which is an accurate answer, reflecting his comprehension and application of the concepts of unit price and percentage embedded in price bulletin—"12% discount for ordering 6+ bricks"). He successfully obtained 10 bricks via mathematical reasoning. Yet when he proceeded to purchase the next construction item, he resumed guessing plus trial and error, by entering an estimated initial value and then increasing it by 5 post each failed trial. He spent around 3 minutes guessing, got stuck, appeared frustrated, and still showed no intention to review the price bulletin.

In the above examples, guessing coupled with trial and error was the primary play strategy. The participants appeared to dodge mathematical reasoning and calculation during the trading action, until being prompted or when they realized that mathematical practices were indispensable or more efficient for problem-solving.

In some other cases, participants were engaged in logical reasoning without applying mathematical knowledge or accurate calculation, as the following examples demonstrated.

> Andy placed one of the smallest and one of the largest families into the first container, while inspecting the family inventory chart during the allocation action. For the second and third containers, he continued the same strategy – matching the smallest family with the largest one in the to-be-assigned list and placed the pair to each container. He commented, "I think I get it. So I still have four more families and three more containers." He finished allocating each of the remained largest family to each of the remained two containers to pass the level, "Oh, Yay! Oh, Yay! I beat it! Oh, Yay!" He was very excited, waving and clapping the hands.
>
> George started by assigning the biggest family to each container. He did not process the statements on the unit and ratio governing family members' living space needs in the task description. Neither did he perform any mathematical calculations. He tried to place two second-largest families into another container, failed to do so, and then replaced one with a smaller family. For the next container, he tried adding the second-largest family, and then the smallest family. He repeated the same strategy for the fifth container. He went to the last container and remarked, "I think I am going to do it this time!" He managed to add the last family to the last container, and got a Congratulations screen, "YES!" His neighbor asked, "How did you do it? How many (containers) did you put?" He answered, "Put the big one (container) on the bottom, and the fairly big one on the top." He did not realize that the two containers he referred to actually have the same living areas.

As shown above, participants were involved in generic logical reasoning about the space allocation, such as evaluation, information mining, planning, testing, and solution refining. Yet these reasoning processes did not involve ratio- and area-related mathematical calculations.

[1] All participants' names cited in this paper are pseudonyms.

Notably, there was a pattern of *failure-driven learning* among participants: recurrent failures resulting from fluky psychology, guessing, or generic reasoning would trigger the acts of mathematical knowledge application and calculation. The game behavioral analysis data indicated that the percentage of explicit content engagement in the participants' gaming actions usually doubled from the earlier gaming sessions to the later ones.

*Prioritizing problem-solving efficiency* There was an observed association between the perceived value of mathematical solutions and participants' engagement in endorsing those solutions for game problems. In other words, when the evaluation of game performance prioritized efficiency, it motivated the players' exploration of mathematical solutions. Such a pattern is illustrated by the following example.

> Rather than estimating or calculating the amount of bricks and other building materials beforehand, Sandy was ordering those items as needed during the construction process. She would order four bricks initially, stacked them as a row along the foundation, and then went back to order another four bricks.

What Sandy did was repeated by multiple other participants. Game conversations among participants indicated two main reasons underlying the act of repetitively ordering a small set of items: (1) avoiding the act of calculating the amount of needed items based on the unit size of an item and the targeted living area of the structure to be built and (2) avoiding the processing and application of percentages (e.g., 6% discount for ordering 6+ bricks each time) for the cost calculation. These participants apparently deemed preplanning for building (that frames mathematical thinking and calculation) as effortful and unnecessary when tackling a game challenge.

The dodging of mathematical planning and reasoning, prominently, was curbed by the introduction of action-specific rules that prioritize problem-solving efficiency—the "time limit" and "material credit" as the reward or evaluation criteria of a building action.

> Sandy managed to complete the four walls surrounding the foundation along with the door and two windows. She went back to the virtual store to order more bricks to build the roof, but got a pop-up window notifying that she had run out of the material credit. The second time when she tried the task, she started to order 10 bricks each time and computed the cost with the discount rate included during the trading action. She was almost done with building, yet failed the level again for exceeding the time limit. The third time she tried the task, she read the price bulletin board carefully, used a paper sheet to preplan and calculate the number of bricks used for each side of the wall around the foundation, pre-ordered the doors and two windows, and entered an accurate value for the cost of a batch of bricks in the ordering area. This time Sandy managed to pass the game level. And while she complained to her neighbor how challenging the task was, she instantly went on to play the next game level/task.

As Sandy's case shows, only when mathematical planning, calculation, and reasoning are warranted for gameplay and perceived as high-paying strategies to tackle game challenges would they be implemented. Game rules that prioritize efficiency and preplanning in the action-specific evaluation would frame the associated mathematical solutions as the most anticipated strategy and hence help to foster participants' situational interest, commitment, and potentially a positive disposition toward mathematical problem-solving.

*Reward versus punishment with trade-off between ruling and inclusiveness* When experimenting with game action-specific rules, we found that setting a time limit with a standard threshold is challenging, because individual learners differ in both play fluency (e.g., of maneuvering 3D objects or comprehending the gameplay rules) and math problem-solving competency. A standard time limit tended to punish learners who do not have much gaming experience or are not confident about game-based math problem-solving. Frequently, participants complained that they were just "one brick away from the success" when they were timed out. Although failure-driven learning appeared to promote cognitive and content engagement in gameplay as discussed above, iterative failures due to the time limit appeared to discourage participants who needed scaffolding or a lenient environment for alternative types of game-based learning. Some participants, for example, were observed working on the game problems offline using paper sheets, exchanging strategies with peers, or asking for help from a facilitator or teacher amidst gameplay. These actions, though potentially extending the on-task time, are part of game-based learning and valued cognitive or affective support for the participants.

A similar issue is the level of "forgiveness" toward the minor defect in the player's action-specific performance. When evaluating the players' design solution against the preset evaluation parameters (e.g., thrifty in material cost and time, reproducing the shape, size, position, and functionality of the target structure and the resource usage rate), setting the necessary degree of accuracy relates to the gauge of an optimal challenge for learners. For example, in a shelter-building task, the game evaluates whether a built structure is adequately secured against a sandstorm, by testing whether any single particle would blow through the walls/roof to touch the foundation. The size of the particle can be up- or downscaled to test the strength of the structure. We found that a low level of "forgiveness" tended to punish the participants who have a lower level of fluency in maneuvering 3D objects (e.g., bricks) but comparable in the action-related math competency than others. In other words, these participants could produce the output that is accurate in its mathematical properties but defective in its design features (e.g., having a half-inch seam in between two bricks on the roof) due to an inept performance of brick stacking. Executing a standard level of accuracy across all design evaluation parameters would hence create a conflict between content and technical competencies for individual learners. Moreover, we also found in certain cases, a high-fidelity evaluation of certain design parameter (e.g., the sturdiness of the structure or whether it will collapse given a seismic wave) would involve the evaluation and hence the exploitation of the resources of physics knowledge (e.g., force, friction, elasticity, mass, and joint) that is beyond the project scope and the expected knowledge base of the middle-school users.

Consequently, we have refined the rules on time and material cost as rewarding rules rather than the pass-or-fail punishment. Specifically, badges of different criterion categories (i.e., time and material credit) will be awarded to players who outperformed the threshold value in each category. A relatively lenient, minimum requirement of design evaluation is set to encourage learner agency in the initial game levels, with the level of accuracy gradually scaled up in more advanced game levels when the players are expected to develop an appropriate level of fluency with gameplay in addition to game-based math problem-solving. The design parameters that leverage an out-of-scope knowledge base were detached from the ruling base for game action evaluation. The infield testing of the refined game action rules on participants' game-based problem-solving and learning has supported our design decisions (Ke et al., 2017).

### *4.3.3 Designing Intermediary User Interface*

Learning in E-Rebuild is to proactively interact with, interpret, and coordinate multimodal elements of a building-oriented mathematical phenomenon or problem, by selecting, studying, and maneuvering these elements to map out their relationship and finally configure the problem solution. The interface that enables players' active and meaningful interactions with the problem elements (or game objects) is hence a main facet of our design exploration and has been iteratively developed, tested, and refined.

An important user interface in E-Rebuild is the controls for viewing and navigating the 3D game world. To enable multiple perspectives and alternative modes of inspecting game objects (or game-based math problem elements) and hence foster representational flexibility in game-based math learning, we had to leverage both keyboard and the mouse for the control of navigation: using arrow or WASD keys for moving, right click and drag to turn/rotate the direction/angle of viewing and moving, and the scroll (mouse) wheel to zoom in/out. These navigation controls, we found, were novel to users who are not familiar with 3D gaming or virtual world environments. Middle-school players who were used to touch pads faced a learning curve in controlling the keyboard and mouse simultaneously, though they all managed to master and use these controls naturally after playing through five to six orientation levels. The comments like "change your (viewing) angle," "turn the position of your camera," or "move up and to the other side" were frequently heard during the players' game talk, when they tried to mentor each other on how to inspect or enter an object or structure in the game. These comments reflect their effort and cognizance in interpreting, tracking, and positioning objects or benchmarks in this 3D virtual world. Those user controls, though not very intuitive, activated a conscious practicing and reasoning process of the participants in inscribing spatial relationships among 3D structures or objects while shifting the perspective and field of view. That is, they may lack technical efficiency but present pedagogical or learning affordance for the learning game.

Such a pattern governing the integration and trade-off between *technical and pedagogical usability* (i.e., being intuitive versus cognizant) is also observed for the design of user controls for the building actions, such as moving, rotating, stacking, joining, and copying/pasting building items. Different from other 3D sandbox games, object maneuvering and building in E-Rebuild need to follow the basic laws of physics to reflect the "rebuild" theme; thus the objects will collide or rebound with other objects. Moving, rotating, and stacking physical objects in the xyz coordinate axis system to constitute a structure are indeed challenging for middle-school students. Participants in the initial gaming sessions were frequently found either struggling in selecting the appropriate coordinate axis for moving or rotating an object, stressed out when having to frequently shift the viewing angle to move and position the object accurately to the target spot in a 3D space, or frustrated when trying to stack the object over others yet accidently colliding objects. But there was an obvious increasing trend in participants' fluency and accuracy levels in maneuvering the 3D objects during gameplay. The gaming behavior analysis indicated that the average error rate (the percentage of failed or unintended trials in all observed rotation acts) of the user control with object rotation was 0.40, and the error rates with other building actions (e.g., moving and stacking) were 0.15 to 0.16. The high error rate with the object rotation control, on one hand, could be due to the low technical usability of the interface—it needs time for the player to take on the keyboard shortcuts ("Tab" for shifting among the three axis coordinates, "," and "." for clockwise or anticlockwise rotation). On the other hand, it showed that the middle-school students were in need of training in the 3D rotation task for the spatial skills development. We found that the *intermediary* interface actually had necessitated a conscious performance of preplanning and extrapolating the specific axis and direction to rotate or move an object before actually trying them out, since instinctive guessing would involve significantly more clicks and hence more effort for the player. The infield studies have demonstrated that E-Rebuild participants, in comparison with the control group students, demonstrated improved mental rotation task performance (Ke et al., 2017).

To improve the technical and pedagogical usability of the intermediary interface of building, we added a joining and a copying/pasting function. These two functions enable the players to join neighboring items into a panel or a structural subsystem, copy/paste it to create multiple panels or subsystems, and then compose them into a complicated structure. This "panel" approach, in comparison with the "brick-by-brick" approach, is not only more efficient but also fostering the performance of design planning before building. For example, when building a multiroom adobe house or a stadium bench, the players would find it difficult to adopt a "brick-by-brick" approach. When they resorted to the "panel" approach, they got to analyze the structural subsystems of the house or the bench (e.g., foundation, walls, and roof; support structure, seating, and railings), calculate the configuration of the subsystems (e.g., number of bricks, size, and shape of each subsystem), and gauge the number of bricks needed in the inventory to copy/paste a panel or substructure. In other words, the players have been engaged in composing and decomposing three-dimensional shapes and building-related mathematical calculation, when using joining and copying functions for building. It should also be noted that both functions involve only left clicks (to select the neighboring items to be joined) that are assisted with visual cues (with the selected items highlighted) and are found high in technical usability (with a low 0.07 error rate average).

In certain cases, we had to prioritize the learning affordance of a user interface to its technical usability. In the allocation action, for example, we found that the left click, button control (e.g., "+" and "-" buttons) for adding or removing an item to an enclosed space (e.g., allocating families to the shelter or fishes to a pond) was significantly and positively associated with the guessing and trial-and-error gaming strategies. Instead, the mechanism of drag and drop the items by unit from a personal item inventory to the target space tended to reduce the behaviors of wild guessing. It is because the drag-and-drop act is more dynamically linked with the visualized consequence (e.g., a four-member family being dragged/dropped to physically occupy part of the space), thus promoting participants' awareness of the relationship between occupants and the space to better comprehend the math problem to be solved.



## 4.4 Game World Design

In our design and research of E-Rebuild, we have focused on particularizing a backdrop mission via the spatial narrative, or environmental storytelling, of the game world in which the narrative element is infused into a space that a player navigates through and interacts with. The game world presents multimodal, contextualized representations of a mathematical problem via a series of background scenarios or landscapes, interactive game objects and structures, game characters, and landmarks. It helps to (a) legitimize and motivate architectural design-based mathematical problem-solving activities and (b) embody a multimodal problem space that portrays dynamic beginning, intermediate, and goal states in consequence of the player's problem exploration and solving actions.

### *4.4.1 Game World as the Scenario for Contextualized Problem-Solving*

The overarching mission in E-Rebuild is to design and rebuild a disaster-damaged space to fulfill the design parameters and varied residential needs specified by various architectural scenarios. These architectural scenarios were presented via diverse landscapes (or environment settings) along with associated "rebuild" themes, such as a post-quake island with a shelter to be built, a desert with adobe houses threatened by the sandstorm, an urban school site with portable classrooms and a stadium to be restored, or a rural farm with livestock shelters to be constructed against predators. These environment settings, with the focal points (or landmarks) and other objects (e.g., building materials, tools, and other structures and props) on the set, were designed and developed by the architect and game designer collaboratively. The architect in the team first designed the layout and visual content of a series of environmental settings using Google SketchUp (as Figs. 4.3, 4.4, and 4.5 exemplified). The game designers then simulated and developed these settings in Unity 3D.

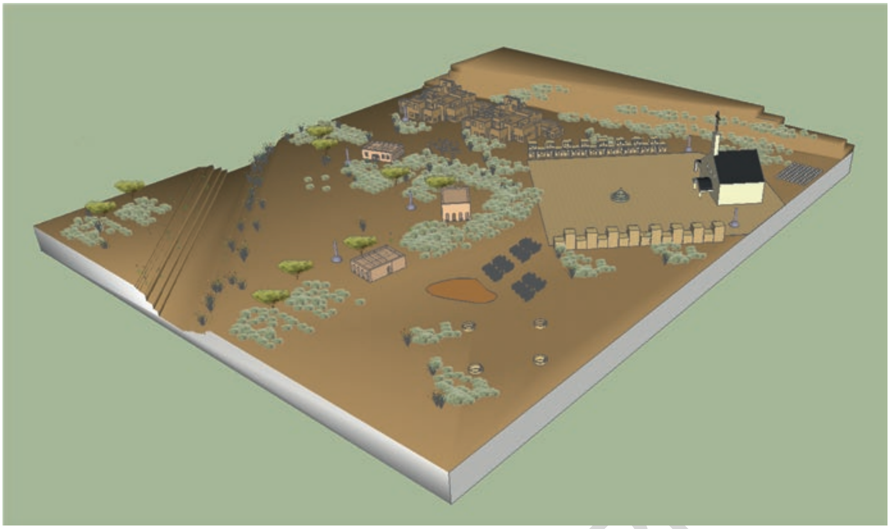

**Fig. 4.3** Desert and historical rural pueblo

**Fig. 4.4** Rural farm

When developing environmental settings, we tried to reproduce the similar level of fidelity and visual aesthetic appeal of the architect-designed sets and landscapes. Yet when we infield tested the prototype with the students at the local school district, the high-fidelity game worlds loaded very slowly using the school network and was conflicting with the older version Chromebooks used prevalently in the school classrooms. To better design the game as a learning tool compatible with the existing IT

**Fig. 4.5** Urban school

infrastructure of the school setting, we scaled down the level of fidelity as well as the scope of map and adjusted the visual presentation as a conversion between the original design and the typical sandbox game world (e.g., Minecraft). We found that a lower level of fidelity in the game world design did not reduce the engagement level of the participants. Actually, the downscaled map and game space helped to focus players' attention on the at-hand task rather than exploring the virtual world. For example, a heat map analysis with the players' navigation behaviors in the original game world demonstrated that the most frequently visited or explored parts of the set were not the construction site or the focus point but boundary spots (e.g., underwater ditches or mountains) that were irrelevant to the problem or learning task. Such an off-task game space exploration behaviors dropped by 50% in the simplified game world version.

In addition to the implicit storytelling—background scenario presentation—via the game space, we used a task panel to present a description of the game environment story associated with a game episode (comprising multiple levels with the same set/landscape) and game level-specific objectives. We tried to make the task description concise, dialogic, and chunked because the infield testing indicated that middle-school players tended to spend least time reading texts on screen during gameplay.

## 4.4.2 Game World as the Problem Space

A theoretical conjecture for E-Rebuild design is that meaningful interactions with multiple forms of external representations will convert an individual's mental representation for mathematical problem-solving to the sense-making process in which relevant cognitive structures are experienced richly, multi-encoded, and integrated flexibly. Given this conjecture, the game world will act as the externalized problem space that animatedly portrays the beginning, intermediate, and outcome states of problem-solving, via interactive game objects and dynamic visualizations (e.g., visual cueing, feedback, and altered states of objects) in response to players' interactions with these objects.

In E-Rebuild, each math problem is represented in multimodal forms in the game space. These multimodal external representations include (1) a *verbal/syntactic task description*, including mathematical and design vocabulary and syntax; (2) *pictorial presentations*, including interactive 3D game objects (e.g., varied types of construction items and the target structure), 2D diagrams (e.g., a floor plan), and a spatial configuration of the landscape designating the location, size, and direction of the structure to be built; (3) *formal mathematical notations* embedded in the task description, inscribed onto game objects, or presented via cursor-on-target cues; and (4) *concrete stimuli*, such as a ruler that measures distance and angles.

Given these multiple external representations in the game world, students must actively investigate, transform, and integrate them into a coherent, internal problem representation to arrive at the solution. In E-Rebuild, core game actions, such as *site survey*, *item collection*, *trading*, *building*, and *allocation*, are designed to necessitate active encoding of the external mathematical representations. The gaming objects in the game space, in addition to the game actions and rules, collectively frame and foster game-based mathematical problem representation and solving processes, ranging from processing and selecting information needed to selecting, testing, and refining mathematics-related problem-solving strategies. In summary, students' internal mathematical representations can be altered with each interaction with the game world and interactive game objects and linked automatically and continuously to one another to facilitate mental model development.



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# Author Queries

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# Chapter 5
# Interweaving Task Design and In-Game Measurement

**Abstract** There are two important design issues related to game-based learning (GBL) in school settings: (a) the intrinsic integration of content-related tasks in gameplay and (b) the real-time capture and analysis of in-game performance data. In this chapter, we describe an integrative design approach that is aimed to interweave game-based task design with in-game assessment of learning. Extending other GBL projects in which the mechanism of data mining for assessment was created *after* game development, in E-Rebuild we have designed the evidence-centered, data-driven assessment *during* the course of game design. Design-based research findings on emergent core design processes and functional conjectures on the approaches of task generation and evidence accumulation are discussed, with support of infield observations on the implementation feasibility and outcomes of various design assumptions.



## 5.1 Introduction

In E-Rebuild, we examined two important design issues related to game-based learning (GBL) in school settings: (a) the intrinsic integration of content-related tasks in gameplay and (b) the real-time capture and analysis of in-game performance data. In spite of the plethora of research on GBL, the design descriptions or operational conjectures on how to develop and integrate domain-specific learning tasks in gameplay are scarce (Habgood & Ainsworth, 2011; Ke & Shute, 2015). In addition, learning in games has generally been assessed via external tests in a post hoc manner (Shute & Ke, 2012). Adopting an educational data mining approach, real-time assessment of learning based on the dynamic performance of players could better capture process- and performance-oriented evidence on competency development (Shute, Ke, & Wang, 2017). This has the potential to drive the design of personalized or adaptive game-based learning while not being intrusive to distract players' gameplay or state of flow.



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In this chapter, we review an integrative design approach that intends to interweave game-based task design with in-game assessment of learning. Different from other GBL projects in which the mechanism of data mining for assessment was created *after* game development, in E-Rebuild we designed the evidence-centered, data-driven assessment *during* the course of game design. Design-based research findings on emergent core design processes and functional conjectures on the approaches of task generation and evidence accumulation are discussed, with support of infield observations on the implementation feasibility and outcomes of various design assumptions.

## 5.2 Conceptual and Design Perspectives

### *5.2.1 Content Modeling for Game Task Design*

Games in general can be defined as organized play that is structured by a set of rules and an obstacle-tackling goal (Klopfer, Osterweil, & Salen, 2009; Schell, 2014). A long-held concern about using computer games for learning is that students may be distracted by the play part, thus not achieving the learning goals (Miller, Lehman, & Koedinger, 1999). It is argued that the extent to which the content is intrinsic to the game tasks and associated actions, rules, and goals will influence the game's learning effectiveness (Richards, Stebbins, & Moellering, 2013). Nevertheless, empirical and theoretical research examining the design of an intrinsic integration between learning and game tasks is still limited and inconclusive (Habgood & Ainsworth, 2011).

A recent review on the design of intrinsic integration of domain-specific GBL (Ke, 2016) argued that it is critical for a learning game designers to clarify what, how, where, and when learning and content will be embedded and activated by gameplay actions, rules, and game world or narrative design. Successful integration of learning in games is regarded as a process rooted in an exploration of content or learning elements that are fundamentally engaging within an academic discipline and represent meaningful interactions between the player and the epistemic frames—salient activities, understanding, and value—of the target subject matter (Shaffer, 2006; Klopfer et al., 2009). These engaging learning elements should provide players with legitimacy in content engagement (Barab, Gresalfi, & Ingram-Goble, 2010). Therefore, meaningful game task design should be driven by content modeling, a process of defining the ontology of the targeted subject domain with a mapping-building-block notion. During the content modeling process, componential concepts and skills (or competencies) along with their associated resources, properties, and examples (e.g., conceptual representations or skill demonstrations), as well as the relationships between these componential competencies, are specified and presented via cognitive mapping.

### 5.2.2 *Integrative Design of Task and Assessment*

From the perspectives of construct-centered assessment (Messick, 1994) and evidence-centered design for educational testing (Mislevy & Haertel, 2006; Almond, Mislevy, Steinberg, Yan, & Williamson, 2015), task construction operationalizes the underlying cognitive theory and the proficiency model of the targeted competencies and hence is a core part of the assessment design. Task construction follows the operational definition of targeted competencies and the analysis of behaviors that reveal the competencies. Thus the selection or construction of relevant tasks that are intended to elicit those behaviors is based on evidence, and interacting with such tasks serves as both the source and evidence of knowledge and skill development.

The literature of learning and assessment highlights the following two salient claims for the integrative design of specific tasks and the overall assessment: (a) the core of authentic tasks is to simulate the representative challenges and criteria of the real-world application of target competencies (Wiggins, 1990) and (b) the performance of complex skills (e.g., those of mathematics and science) is moderated by contexts, and hence it is necessary to construct cross-contextual tasks with varied difficulty and implementation contexts to effectively measure skill development (Resnick & Resnick, 1992).

### 5.2.3 *In-Game Integration of Active Learning and Authentic Assessment*

Games and simulations can be instrumental in the aforementioned task and assessment design processes because they can (a) present a broad range of complex scenarios and tasks to model the functional context of the real world, (b) enable interactions with authentic tasks and contexts, and (c) achieve a comprehensive, cross-contextual assessment of the complex skill. For example, the conventional approach to designing math word problems typically "attempts to strip the problem context of all irrelevancies, retaining only the task information needed to engage the focal knowledge and skills involved in task processing" (Messick, 1994, p. 18). Yet task-based skill practice and assessment are subject to the moderation of context variables. Game-based challenges, presenting controllable and customizable criterion situations to simulate varied authentic task contexts, can afford the assessment of math development that ranges between situated knowledge and abstract, decontextualized understanding (Pratt & Noss, 2002).

#### 5.2.3.1 Data-Driven, Game-Based Assessment

Process-oriented data mining and learning analytics methods, such as Bayesian networks, social networks or structural analysis, visual or graphical analysis of event paths, and sequential analysis of time series, can capture the complex and open-ended learning trajectories in a game setting. Prior research has suggested that educational data mining and learning analytics can and should be used together to exploit game-based performance data to inform on students' on-task or off-task behaviors, competency development related to the targeted subject matter, and hence the effectiveness and design of learning games. Four recent projects (Dede, 2012; Levy, 2014; Shaffer et al., 2009; & Shute & Ventura, 2013) have exemplified the potential and applicability of game-based assessment via educational data mining. These projects all adopted a data-intensive, evidence-based approach by collecting, measuring, analyzing, and reporting dynamic data about learner performance and contexts (e.g., online log data) to understand and optimize learning and the environments in which it occurs. Multiple methods of data analyses (e.g., quantitative psychometric modeling, network or structural analysis, and path analysis) and visualization (e.g., algorithms, models, network graphs, or spatial and chronical maps) were used. On the other hand, in some previous projects, data-driven assessment design tends to be a post hoc justification or evaluation for the game development.

## 5.3 Design-Based Inquiry

Adopting the design-based research approach (Sandoval & Bell, 2004), we explored, iteratively tested, and refined the core elements and design features of the game task and assessment of learning through multiple mixed-method case studies. The successive iterations and testing played a role similar to that of systematic variation in a controlled experiment (Cobb, Confrey, Lehrer, & Schauble, 2003). Specifically, the design-based investigations focused on extracting design heuristics that would enable an integrative design of task and in-game learning assessment, by addressing the following questions:

- What are the core processes that define the integrative design of game tasks and assessment of learning?
- What are the functional conjectures on the design strategies and features of the GBL tasks and assessment derived from the iterative experimental findings?

Extensive, longitudinal data sets were collected during the course of our design experiments. These data sets involved qualitative and quantitative resources, including participatory observations of the project team's design meetings, screen- and video-recording of participants' gameplay actions/reactions, game activity logs, participants' gameplay think-aloud transcriptions, interview data, and results from math knowledge tests. One hundred and twenty middle-school students participated in the E-Rebuild learning program and test-played the prototypes of the GBL assessment system that was iteratively and systematically refined based on the successive design-based research findings.

We conducted retrospective analyses (Cobb et al., 2003) with the longitudinal, design experiment data to generate situated accounts of design conjectures (Schwandt, 2007; Sandoval & Bell, 2004) and to specify the functional contexts of those conjectures. Specifically, we conducted thematic analysis using the design meeting records, coded the gameplay recordings to delineate the types and properties of major gameplay actions and reactions via behavior analysis (Ke, 2017), and then extracted the descriptive data (e.g., attempts made, levels passed, and time spent) from students' gameplay activity logs. Students' gameplay activity logs, as well as their pre- and post-gaming math knowledge test results, were also used to calibrate and refine the game-based learning evidence and assessment models to validate the game-based assessment mechanism.

## 5.4 Core Design Sectors for In-Game Learning and Assessment

The process of interweaving game-based task and assessment development in E-Rebuild includes five core design sectors: (a) designing templates of tasks based on the selected gaming (i.e., architectural design) actions that *necessitate*, as well as the scenarios (i.e., overarching design missions) that *frame,* the practice of the targeted competencies; (b) setting the gameplay rule and reward system that scaffolds mathematical practices; (c) developing and organizing tasks based on the competency, evidence, and task models; (d) drafting the game logs, including the specification of in-game performance observable variables, along with the assessment statistical model (e.g., a Bayesian inference network); and (e) testing, refining, and validating the feasibility and effectiveness of the tasks and assessment models. The ordering of these core design sectors refers to their operational sequence in our game design process. However, they frequently interact with each other, thus yielding a holistic system rather than a collection of segmented processes.



### *5.4.1 Designing Task Templates: Action-Oriented, Scenario-Based, and Math Practice-Necessitating*

#### 5.4.1.1 Action-Oriented, Contextualized, and Multimodal Mathematical Problems

Our design-based investigation indicated that participants' gaming actions (i.e., the core part of gameplay and main behavioral unit to be tracked in gameplay performance) underlie the nature of the math content (e.g., qualitative understanding, numerical calculation, and expressions and equations) and hence the targeted GBL actions (e.g., identification, procedure execution, and problem-solving). Via iterative expert review and user testing of various architectural design actions (as described in Chap. 4), we have settled on a set of architectural design-based actions: (a) collecting and customizing construction items, (b) site surveying and building, (c) material trading, and (d) space and resource allocation. After composing these learning-constructive game actions and incorporating relevant backdrop design scenarios, we then developed an assortment of game task archetypes.

In E-Rebuild, each task template was designed to depict an archetype of contextualized math story problems. These problems aim to motivate learners to investigate and coordinate alternative representations of the constituent math parameters, variables, and relations to solve a realistic design problem. The architecture-themed scenarios served to contextualize the final construction of tasks and the development of task narratives. For example, a task in E-Rebuild asks the player to rebuild a multiroom structure by referring to a pre-earthquake house model and using a minimum number of shipping containers. The player then must assign different family configurations to the shelter, with the *ratio* of an adult's required living space to a child's required living space being x to y (e.g., 2:1). A multimodal representation of the problem is conveyed through (a) a *verbal/syntactic* task narrative; (b) *pictorial presentations*, including 3D game objects (e.g., shipping containers of different sizes and the house model), 2D diagrams (e.g., the floor plan and a material price board in the form of a table of equivalent ratios), and a spatial configuration of the landscape designating the location, size, and direction of the shelter to be built; (c) *formal math notations*, such as ratios embedded in the task narrative, numerals inscribed onto game objects, and operations presented via gameplay feedback and the help panel; and (d) *concrete stimuli*, such as cutting and scaling tools and a ruler.

Given such a *multimodal math story problem*, the player needs to actively investigate and transform math representations embedded in the game world and then select and integrate the information into a coherent problem representation to arrive at a solution. In E-Rebuild, core game actions necessitate active encoding and coordination of external math representations. For instance, a single "*building*" game action involves the acts of *planning* (e.g., site survey or measurement, floor or landscape planning via object positioning), *composing and decomposing* (prisms, such as joining and stacking cuboids), *covering* (the space, such as painting an area), *surrounding* (a structure, such as fencing a yard), and *filling* (the cavity, such as filling a rectangular prism with unit cubes or spheres). These actions will activate participants' interactions with the verbal, graphical, and numerical representations of a geometrical figure and facilitate a coordination among these mental representations.

#### 5.4.1.2 Core Elements and Properties of a Task Template

Task archetypes can be classified based on core gameplay actions, such as collecting, building, trading, and allocating. Certain task types, such as building, could also encompass sub-tasks of planning, composing and decomposing, covering, surrounding, and filling. Each basic E-Rebuild task template integrates a list of key structural elements. These structural elements include (a) the core/driving action and its enabling act(s); (b) action-appropriate goal state of the problem and the criteria conditions that define the satisfactory goal state (e.g., rebuilding a pre-quake house model with a minimum number of items); (c) start state of the problem, including unsatisfied criteria condition(s) in comparison with the goal state;

and (d) obstacles to be resolved or tackled to achieve the satisfactory goal state. Obstacles will consist of action-specific constraints (e.g., limited space for an allocation action or limited materials for a building action), sub-goal hierarchy, objects to be maneuvered (e.g., actable objects), and/or those to be explored (e.g., properties of the structure to be built and construction materials).

Prior research on problem structures (e.g., Kaller, Unterrainer, Rahm, & Halsband, 2004) and mathematical problem-solving (e.g., Schoenfeld, 2014) has shown that the difficulty of a task archetype can be predicted by the requisite math knowledge and skills needed to solve the task, as well as the structural features of the task, like the number of constraints—where more constraints mean that more variables need to be considered during problem solution. Another task feature which can influence its difficulty concerns the ambiguity of goal hierarchy (i.e., the obscurity of goal priorities in the assembly of sub-goal states). Finally, the existence of suboptimal, alternative solutions in a given task renders it more difficult to solve. Overall, the prerequisite math knowledge in a given task archetype reflects the required level of competency in the content domain, while the task's structural features affect math problem-solving performance, including problem interpretation, problem-solving strategy selection (or planning), execution, and monitoring.

#### 5.4.1.3 Composing Tasks for Game Level Development

E-Rebuild is a multi-episode game. Each game episode then consists of multiple levels. A game level can be developed as either an architectural design problem with multiple instantiations of task archetypes or as a sector of an overarching inquiry (i.e., episode) which carries only one instantiation of a task archetype. We have experimented with these two options of task composition for game level development and found that the former was challenging for novice student players who lacked skills related to problem interpretation, sub-goal generation, and analysis. In addition, a typical duration of a class session (and hence the in-class gaming session) was only 45 min, which made it difficult for learners to fully practice and complete a comprehensive inquiry-based game level. To bolster engagement in the game and learning, we found it necessary to simplify the task composition by further decomposing a task within a game level.

Our initial game level prototype (referred to as "row house") illustrates our design decisions governing task composition. Figure 5.1 depicts the game level which serves as the backdrop (or design inquiry) for the player who has to build a shelter for survivors using shipping containers. The design inquiry consists of three types of tasks—*collecting* (survivors and building materials), *building* (a shelter), and *allocating* (survivors to the shelter built). During collection, the player is expected to calculate the space needed to accommodate each type of surviving family (i.e., the various adult-child ratios in the family composition and associated space requirements), measure the living space (area) afforded by each container, and then figure out the number of containers needed before collecting both survivors and containers within a limited time frame. During building, the player is

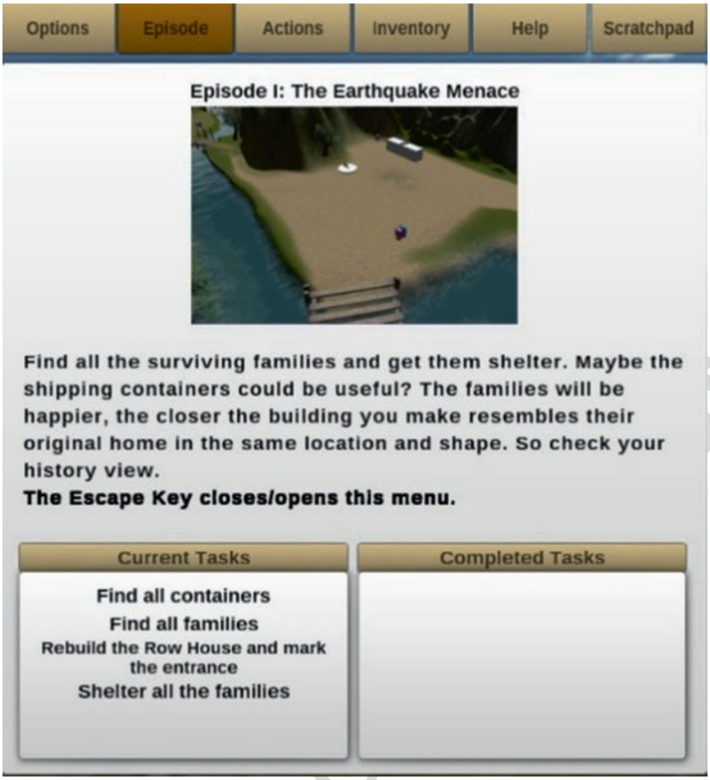


Fig. 5.1 Composition of tasks in a game level



expected to review the location, three-dimensional shape, and size of the pre-quake structure and replicate it using collected shipping containers. During allocation, the player then has to allocate the various families into the limited number of container rooms in the shelter. For each type of task, multiple constraints are applied, such as the variety and number of types of families and containers to collect, the time limit, the design criteria, and the space limits per room compared to the space needed by the different families. Additional constraints may be added to further increase difficulty, such as minimizing the transportation cost of collecting a container.

In the earliest version of "row house," all component tasks were presented as a holistic inquiry without in-game feedback or cueing on the composition of subtasks. During its infield testing, we observed that middle-school students typically lacked the awareness or skill to identify and plan sub-goals for the inquiry. They were quick in figuring out how to collect families and containers yet failed to purposefully check and calculate the space needed per family or use the family collection results to plan the container collection act. Hence they would randomly collect containers and then either not replicate the row house or build the structure but not allocate all of the families given the wrong number and/or type of containers collected. To scaffold their sub-goal generation, we decomposed the broader inquiry into segments and had the game check the player's collection performance before allowing him to proceed to the next step/task (as Fig. 5.1 illustrates). A consequence of such a linear segmentation, however, was that certain players adopted the generic strategy of guessing, along with trial-and-error actions to pass the collection sector, rather than processing and applying the task-related math information. Segmentation also caused players to inadequately develop an overarching interpretation of the problem. For instance, they failed to recall the living space needs of the different families (i.e., information identified in the collection sector) during the allocation sector. We additionally experimented with task-equivalent game level development, in which each component task represented a separate level. The component tasks comprised a partial problem to solve.

Now, in the game, after the player completes a sequence of related task levels, he then must tackle a complete problem (boss level) which is an all-inclusive instantiation of the sum of component tasks. Correspondingly, we created two levels of game chunking—*level* (task-equivalent) as the child or lower-level units and *episode* (multitask-equivalent) as the parent or higher-level units. Such a mixture of task composition and decomposition to particular actions needed, as the field test data indicated, was well received by student players and associated with an increased level of task engagement and math problem-solving performance.

**Chunked versus holistic task** We experimented and conducted a qualitative comparative analysis with the users' participation behaviors in between the holistic task with which a player had to explore and chunk the componential problem-solving phases by himself and the chunked task series in which each problem was purposefully chunked into multiple phases (or levels) that players will proceed sequentially with. When interacting with the sequenced phases (e.g., material collection/trading, structure building, and space allocation) in a design task, participants followed a framed problem-solving path to solve and connect each part of the puzzle. The comparative analysis of participants' game-based problem-solving processes and performance in the two task structures indicated that an explicitly chunked task structure, by offering partial representation of a complex problem, fostered task engagement. Participants with the holistic task structure demonstrated obviously more off-task behaviors than those with the chunked task structure. For example, participants of the former were frequently found wandering around the game world, casually playing with a game object (e.g., using the measurement tool to draw line sketches instead of site surveying), and reporting feeling stuck or lost during gaming.

On the other hand, an explicitly chunked task structure presented less opportunities for participants to perform failure-driven, reflective learning. For example, with a holistic task, participants were frequently observed recalculating the size of each container, the total living space needed by the families, and hence the number of containers needed, when they failed to allocate all families. Yet with the chunked task structure, such a failure-driven mathematical practice occurred less frequently because at the end of the building phase, the game would evaluate the shelter built and alert the player if containers used were not enough. In other words, the game had done a critical part of the problem representation and solution for the player.

**Connection between tasks** For multilevel episodes in E-Rebuild, we explored alternative ways of constructing and relating game tasks or levels. For example, in an "Island" game episode, every level presented a task following the same problem template, while the specifics of core problem parameters (e.g., the size of a container, the number and type of families, the adult-child ratio in space needed) varied to create incremental difficulty in mathematical problem-solving. In a "Desert" episode, a sequence of levels represented a collection of tasks governed by an overarching architectural design scene. Across the levels there was an incremental inclusion of new parameters (e.g., new building and site design criteria) in the problem to create incremental complexity in problem-solving. The gaming behavior analysis and infield observation did not reveal any obvious difference between the two task or level arrangements in relation to players' task engagement or game-based problem-solving performance.

Instead, we observed that the degree of granularity required by a building task (e.g., building a structure using prefabricated shipping containers versus using 2-by-2-meter blocks) in different game episodes moderated players' performance in 3D object maneuvering. It was reported and observed that the acts of rotating and stacking 3D objects in a higher granularity level were more time-consuming than that in a lower granularity level. The challenge of manipulating 3D objects during building, interestingly, appeared to foster the behaviors of preplanning for building, such as predicting the rotation and location of a block before placing and stacking it onto another and gauging the minimum space needed or the most efficient way of building. These behaviors were associated with more observed events of mathematical reasoning and calculation.

### 5.4.2 *Setting Gameplay Rules to Motivate Content-Related Task Performance*

Prior analyses of the video- and screen-recorded gaming behaviors of the participants suggested that *intentionality* and *mindfulness* were two prerequisite facets of game-based engagement. Intentionality refers to the ability to create and maintain goal-directed gaming behaviors. Mindfulness refers to the level of reflective thinking (e.g., diagnosing the reason of a failed game action) and degree of planning (e.g., comprehending the purpose of a future game action) during gameplay. The analyses with the gaming behaviors and game logs indicated a positive association between the presence of intentionality and mindfulness in participants' gaming behaviors and game level completion (Ke et al., 2017). The two task engagement patterns appeared to mediate the players' processing and application of in-game mathematical information. Yet even when primary game actions and tasks were purposefully designed to stimulate mathematical problem-solving, players did not necessarily demonstrate intentionality or mindfulness in their gaming moves. Guessing and trial-and-error behaviors were two strategies prioritized by novice players for game-based problem-solving. More critically, their use of trial-and-error and guessing lacked goal direction, mindful planning, reflection, or mathematical thinking. It appeared that novice players, especially those who were motivated to play rather than to learn, were reluctant to accept the circumstance that gameplay in E-Rebuild is an intentional and reasoning process; they tended to avoid much cognitive and mathematical engagement. Therefore, a critical challenge of task design in E-Rebuild as a learning game was to motivate players' intentionality, mindfulness (or cognitive engagement), and hence processing and application of task-related mathematical knowledge (or content engagement) during game-based problem-solving. A theoretical perspective that helps to shed the light on this design challenge is what Schoenfeld (2014) described about the three challenges faced by students in mathematical problem-solving:

> In some cases, "much of the mathematical knowledge that the students had at their disposal, and that they should have been able to use, went unused in problem solving. This was not because they had forgotten it (a matter of *resources*) or because they ran out of time to use it (a matter of *control*), but because *they did not perceive their mathematical knowledge as being useful to them, and consequently did not call upon it* (a matter of belief systems)." (p. 13)

> Students' problem-solving performance is not simply the product of what the students know; it is also a function of their perceptions of that knowledge, derived from their experiences with mathematics. That is, their beliefs about mathematics – consciously held or not – establish the psychological context within which they do mathematics. (p. 14)

In general, Schoenfeld (2014) argued that mathematical problem-solving involves (a) problem-solvers' operational understanding of the mathematical information (or resources at disposal); (b) techniques (heuristics) problem-solvers have or lack for making progress on unfamiliar problems; (c) the way (control) they use, or fail to use, the information at their disposal; and (d) their mathematical world view (belief system) that determines the ways that the knowledge in the first three categories is used. The lack of positive mathematical belief systems actually underlies the observation in our study that players were not willing or had the awareness to access their mathematical knowledge to solve the game tasks.

Based on the infield observations and the aforementioned importance of players' positive perceptions of mathematical information during problem-solving, we speculated that setting gameplay rules that highlight mathematical knowledge application as the most efficient, if not the only, strategy for problem-solving should reinforce mindful and content-related performance in the game. Hence we designed a set of task constraints and reward rules that aim to curtail absent-minded, casual gaming actions and enhance players' awareness of the connections between each math skill-based game action and the reward of gaming progress or credit. For example, during the aforementioned allocation task, players intermittently added families to random containers and used a trial-and-error approach to reshuffle them (families to containers) until the task was solved. Consequently, a material and time credit deduction/penalty was then added for each allocation-reshuffling move. Once the deducted credits hit some threshold, the player has to restart the task/level. With this supplementary gameplay rule for the allocation task, the observed guessing and trial-and-error gaming acts were reduced.

Similarly, in a trading task, the player is supposed to order building items in bulk to gain a discount (in an increasing percentage depending on the amount ordered). Yet players frequently found ways to circumvent the percentage calculation and only order items in part, not bulk. They also did not preplan the number of items to be traded before a building action; instead they would buy items as needed during building. To motivate mathematical information processing and calculation, we enforced a "transaction fee" for each trade made, reduced the default material credit, and increased the distance (and hence transportation time) between the store and construction site. We also added a badge system (in addition to the game level pass/fail) that explicitly reviews and rewards the degree of accuracy and efficiency in a player's game-based problem-solving actions. All of these gameplay rules, as the design-based research findings indicated (Ke et al., 2017), have subsequently motivated and increased the frequency of observed game-based cognitive and content engagement acts, reduced the number of failed game level attempts, and promoted game-based task performance.

### *5.4.3 Generating and Organizing Tasks with the Assessment Models*

A retrospective analysis of the observational data and design artifacts from the E-Rebuild design meetings suggested that game task template generation and task instantiation are confined and substantiated by the development of competency, evidence, and task models for in-game assessment of learning. The sequential record of design events indicated a concurrent, interactive association among the aforementioned task and assessment design processes.

In E-Rebuild, we adopted the evidence-centered assessment design approach (Mislevy, Almond, & Lukas, 2003) to construct game-based assessment. Specifically, we started by defining the claims to be made about participants' math competencies (i.e., competency modeling), establishing what actions or elements of gameplay constitute valid evidence of the claim (i.e., evidence modeling), and determining the nature and form of game tasks that will elicit that evidence (task modeling) (Shute, 2011; Shute & Ke, 2012; Shute et al., 2017). Although assessment design flows from competency to task modeling, in practice it is more iterative. Diagnosis flows in the opposite direction. That is, the learners' performance (recorded by game logs) during a game level/task will provide the evidence or data (e.g., logged scores of observable variables) that are passed on to the competency model, which in turn updates the claims (e.g., probabilities) about relevant competencies. Based on the competency claims made, E-Rebuild, in the long term, can dynamically present adaptive help or personalized game tasks/levels to the player.

The competency model, as a framework for defining the targeted skills and knowledge requirement in the game-based learning system, is a collection (or hierarchy) of competencies that jointly define the ultimate achievement, successful performance, or proficiency. Mapping the task templates with the competency model helps to ensure game-based learning and assessment of the targeted competencies and skills (see Fig. 5.2). The evidence model, presented as a Q-matrix (Fig. 5.3), specifies which elements (or observed performance measures) of major game task archetypes will demonstrate the practice and hence elicit the evidence of competency facet(s) and how they will be combined to afford the learning and assessment of the targeted competencies. The task model, presented as another Q-matrix (Fig. 5.4), states which specific game level/task will provide the evidence for which competency facet(s). The evidence and task models help the design team to (a) estimate whether, when, and what tasks generated will accumulate enough evidence and (b) gauge the difficulty, discrimination quality, and hence sequencing of generated/instantiated tasks across game levels and episodes.

### *5.4.4 Designing Game Log with Observables to Record Game-Based Learning Evidence*

During the course of E-Rebuild design, we designed the game logs to track game-based performance measures intended to provide evidence/data to propagate and validate the statistical model (e.g., Bayesian network) for game-based assessment. Game logs are XML files that are created at the end of gameplay. Since the goal is to assess a participant's competency from how the participant plays the game, information that capture evidence of such competencies are logged in the XML file. The following is the content of an example XML file for user "abc" for the game level "SchoolPlacement02":

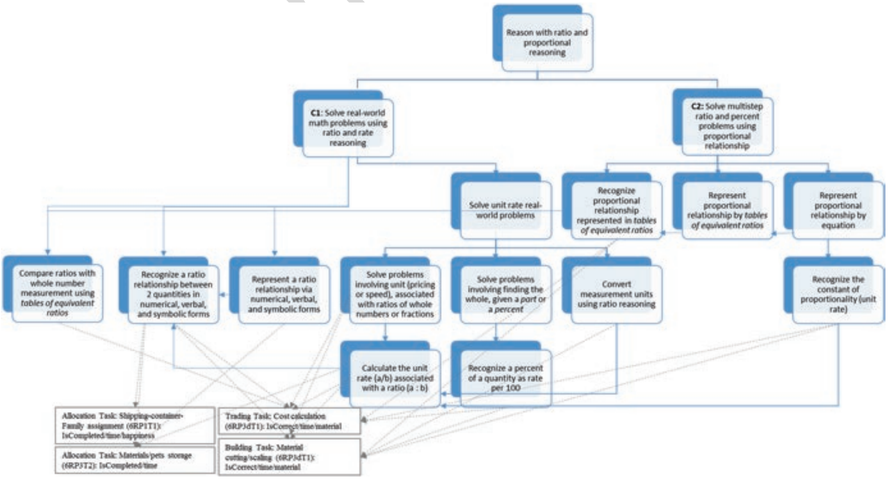


**Fig. 5.2** An exemplary design document depicting competency model and game-based task template design (Shute et al., 2017)

| Task Name | ObsName | Reason with ratio and proportional reasoning | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Compare ratios with whole number measurement using tables of equivalent ratios | Recognize a ratio relationship between 2 quantities in numerical form | Recognize a ratio relationship between 2 quantities in verbal form | Recognize a ratio relationship between 2 quantities in symbolic form | Represent a ratio relationship via numerical form | Represent a ratio relationship via verbal form | Represent a ratio relationship via symbolic form | Calculate the unit rate (a/b) associated with a ratio (a : b) | Recognize a percent of a quantity as rate per 100 |
| Allocation Task | timeToCompletion | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| | Material Credit | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | scratchpad editing(math related) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | assignment operation | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |
| Trading Task | # of trades | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| | scratchpad editing(math related) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | percentage lost in trade avg | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| | cut (for resourcing) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | scale (for resourcing) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Building Task | structure size | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| | structure location | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | structure direction | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | # copy/paste failed | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | scratchpad editing(math related) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | ruler record | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| Game Task | timeToCompletion | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| | Material Credit | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| | Happiness Credit | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |



**Fig. 5.3** Part of an evidence model (Q-matrix) example (Shute et al., 2017). Facets of the focus competency are listed in columns, and the indicators are listed in rows

| Episode | Level | Comprehend a ratio relationship via numerical, verbal, and symbolic forms | Solve problems involving finding the whole, given a part or a percent | Calculate the unit rate (a/b) associated with a ratio (a : b) | (De)compose quadrilaterals and polygons into (right) triangles and rectangles | Compute the area and perimeter of triangle and rectangle | Find surface areas of 3D figures using nets of rectangles and (right) triangles | Compute the volume of right rectangular prisms (V = l w h, V = b h) | Compute area and circumference of a circle using formulas |
|---|---|---|---|---|---|---|---|---|---|
| Island | Collect Container 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Island | Collect Family 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Island | Build Training | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Island | Fill Training | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Island | Build 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| Island | Fill 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| Island | Collect Container 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Island | Collect Family 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Island | Build 2 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| Island | Fill 2 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| Island | Collect Container 3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Island | Collect Family 3 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Island | Build 3 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| Island | Fill 3 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| Desert | Copy Training 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Desert | Copy Training 2 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Desert | Placement Training 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Desert | Build 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| Desert | Angle Build 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| Desert | Location Build 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| Desert | Fill 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| School | Place 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| School | Place 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| School | Fill1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| School | Paint 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| School | Stadium 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| School | Stadium 2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| School | Paint 2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Farm | Angle 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Farm | Perimeter 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| Farm | Area 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| Farm | Volume 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| | | 16 | 14 | 25 | 11 | 17 | 3 | 1 | 2 |



**Fig. 5.4** Part of a task model (Q-matrix) example

```
<?xml  version="1.0"  encoding="utf-8"?>
<root>
<Name>abc</Name>
<Level>SchoolPlacement02</Level>
<Time>40.7275429</Time>
<NumBlocks>0</NumBlocks>
<NumTrades>0</NumTrades>
<TotalLost>0</TotalLost>
<MaterialCredits>10000</MaterialCredits>
<LevelComplete>true</LevelComplete>
</root>
```

The XML file has elements with tags like *root*, *Name*, *Level*, and *Time* which are enclosed within “<” and “>.” For example, <MaterialCredits>10,000</MaterialCredits> is a MaterialCredits element with content 1000. The elements other than *root*, *Name*, and *Level* are the observables for the game level *SchoolPlacement02*.

E-Rebuild prototype has 34 game levels and each level has its own set of observables. Table 5.1 lists a few game levels along with their observables. The last entry of Table 5.1 is the union of the observables from all the game levels. As it is evident from Table 5.1, each game level logs only a subset of the total observables.

### *5.4.5 Testing and Refining Task and Assessment Development*

We have iteratively tested and refined the task templates, including game actions and their interfaces, along with the instantiated tasks via iterative design experiments. To examine the affordance of game tasks in fostering math problem-solving skills and explore the nature of problem-solving processes, we collected longitudinal, gameplay data of participants in every gaming session. Data were collected via

**Table 5.1** Sets of observables for the given game levels

| Exemplary level | Observables |
|---|---|
| 21ContainerCollect | Time, NumWrong, MaterialCredits |
| 26FamilyPlacement | Time, NumWrong, AssignmentComplete MaterialCredits |
| SchoolAssignment01 | Time, AssignmentComplete, NumAssignments, NumFailedAssignments, Num-FamilyCollected LevelComplete |
| IslandBuild02 | Time, NumBlocks, NumTrades, Total-lost, MaterialCredits, distance, size, angle BuildingComplete, LevelComplete |
| *All levels* | Angle, AssignmentComplete, building-Complete, distance, LevelComplete, MaterialCredits, NumAssignments, NumBlocks, NumFailedAssignments NumFamilyCollected, NumTrades, NumWrong, size, time, TotalLost |

infield observations of students' gameplay, informal interviews, game logs, as well as video- and screen-captured gameplay behaviors and think-aloud protocols. We conducted a qualitative thematic analysis with observation notes and gameplay recordings to extract salient themes on participants' gaming actions and their game-based problem-solving processes. These qualitative themes defined the nature of commonly observed and unique player actions, along with the critical properties of each action (e.g., objects engaged, purpose, and relevance to mathematical problem-solving). We then classified them into categorical themes depicting participants' cognitive and affective engagement states and their major gaming actions.

Using the categorical themes and BORIS (an event logging software), we performed pattern matching and systematically coded the recordings of a representative sample of participants' gameplay actions and reactions, using 30 second time intervals as the primary coding unit. The qualitative thematic and systematic behavioral coding results informed about the nature of game-based mathematical problem-solving processes in the context of variant types of game actions and tasks and illustrated the relative effectiveness of each type of game actions, tasks, and gaming interfaces. Based on the analyses results, specific game actions and tasks were then refined and tested iteratively across design experiments.

**Training and Testing of the Game-Based Learning Assessment Model Using Bayesian Network** We have trained and tested the game-based math learning assessment using Bayesian network in Netica. Here are some reasons why we choose Bayesian network for in-game learning assessment in this project:

- It is flexible in allowing domain experts to encode the domain knowledge by defining nodes (i.e., competency and observable variables) and edges (i.e., the relationships among the variables) in a directed acyclic graph.
- It handles missing data. This feature is a requirement in our case because each game level provides only a subset of the observables.

Specifically, we trained, refined, and substantiated the Bayesian network using both users' gameplay data and expert review (Ke & Shute, 2015). Users' gameplay data, as well as external pre- and post-gaming math knowledge test results, were collected during iterative design experiments in E-Rebuild. We consolidated the data stored in multiple XML game logs along with the corresponding pretest scores into a single CSV (comma-separated values) format file. Each entry or row in the output CSV file corresponds to a particular user and her game log for a particular game level played at a certain time. The consolidated data file contains values of different types: integers, strings (categories), and floats. Since we have selected Netica's Bayesian network with discrete nodes for the game-based assessment of learning, all raw values were converted to categorical values. The category thresholds were determined from the training data and reviewed/refined by the educational measurement, math education, and game design experts in the project team (Fig. 5.5).

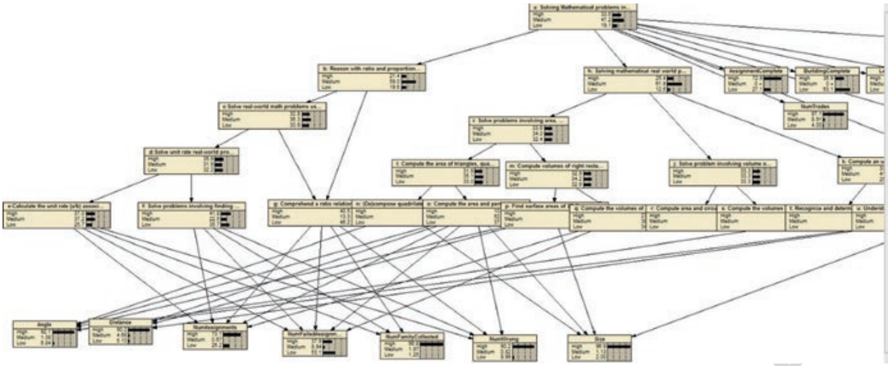

**Fig. 5.5** A snapshot of a Bayesian network model

We used Netica to create the Bayesian network described above and conducted experiments on the preprocessed categorical data set. The goal was to learn a model based on the training set about the relationships between observables across all gameplay and the users' competencies. Later, the learned model can take as input a set of observables from a gameplay of an unknown user and predict competencies of the user.

We fed the training data set into the Bayesian network via the Netica case file format. We chose the expectation-maximization algorithm to train the model. To establish initial values for the conditional probability tables in our Bayesian network model, we considered each level played as an individual case. The initial values for the student's mathematic ability are taken from their external math test results. The network is trained using these values along with the log data. The network is then tested against the posttest data.

After the training was completed, we continued with the testing process. We first created a Netica control file which controls the output we want from Netica. We then fed the testing data set from Netica to populate nodes in the Bayesian networks to obtain the predictions for the participant's mathematical competencies. An association analysis between the in-game assessment results (i.e., Bayesian network predictions for individual learners) and the external post-gaming math test results was conducted to validate the Bayesian network model. The correlation analysis was conducted to examine the consistency between the predicted result of the current Bayesian network model (i.e., low, medium, or high in the targeted competency) and the categorized posttest performance of middle-school gaming participants. The analysis result indicated a significant association, $r = 0.40$, $p = 0.02$. Error rate was used as another matric to evaluate the trained Bayesian network model. The error rate measures the overall accuracy of predictions. The error rate was 0.443 when we validate the model trained on $P_a$ with $P_b$. This shows that the model trained on a certain population can be used to make predictions on an entirely different population.

## 5.5 Summary and Future Investigation

By examining and discussing the task design and assessment modeling processes of E-Rebuild, we were able to explore how the two core game design elements function together to develop a game-based learning system. Such a system can potentially serve as both a learning and an assessment tool. The five core design sectors illustrate the design heuristics of the learning-play integration during game task and level development; data mining-based assessment models for the problem-oriented, task-centered learning; and the non-interruptive assessment mechanism in a playful learning environment. They also support the innate association among content/domain modeling, task template design and instantiation, and assessment model development.

Multiple design issues remain unaddressed and warrant more design-based investigation. The main issues are:

1. The existing game tasks are developed by the project team and cannot afford the activation and assessment of varied sets of math competencies; salient parameters of learning-centered game tasks need to be extracted to inform the generative method to enable cost-effective, scalable, and participatory game task development by teachers and other direct users.
2. The mechanism that enables the real-time collection and analysis of the logged gameplay data needs further development, which will involve the design of an application that dynamically extracts the data from the game logs into the Bayesian network or other applicable statistical models.
3. Incoherency still exists in designing game as a learning tool versus as an assessment tool, in that the sequencing of tasks for learning focuses on scaffolding via a content and difficulty progression and iterative practices for deep learning, whereas the arrangement of tasks for assessment prioritizes selecting tasks that discriminate most and presenting them to collect and accumulate evidence.



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# Chapter 6
# Designing Dynamic Support for Game-Based Learning

**Abstract** The role of support for game-based learning cannot be overemphasized. It remains inconclusive as to what, when, and how support for learning should be designed and implemented to foster learners' extended engagement, in-game performance, and game-based disciplinary knowledge learning and transfer. In this chapter, we review prevalent support features in digital games, prior theoretical and empirical research on scaffolding and support in game-based learning, and the support design conjectures deemed effective. We then share our observations of the obstacles that learners experienced in game-based learning processes when using E-Rebuild, describe the corresponding learning support strategies and features, and report the findings from the iterative testing and refinement of these support features. Propositions for future research and the design of support for game-based learning are discussed in relation to the current project findings and prior research.



## 6.1 Introduction

The role of support for learning in game-based learning contexts cannot be overemphasized (Wouters & Van Oostendorp, 2013). A closely related and frequently examined construct of support for learning is scaffolding. Though the definition and scope of scaffolding is still inconclusive in the literature, scaffolding originally referred to situations "in which the learner gets assistance or support to perform a task beyond his or her own reach if pursued independently when unassisted" (Pea, 2004, p. 430; Wood, Bruner, & Ross, 1976). An adaptive level of support and the fading of the support are implied as intrinsic components of the scaffolding process. In this chapter, we describe our design and research of support for game-based learning in a broader sense that includes both scaffolding with fading (or support as needed) and general learner support without fading. We will use the terms of support and scaffolding interchangeably to include all support features in game-based learning, whether adaptive or general, internal or external.

Support for learning in gaming often involves two alternative avenues: internal scaffolding as the innate design feature of the game (or tool−/material-mediated



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support) and external scaffolding as part of the game-based learning experience or activity (or human agent-mediated support). Research on the desirable implementation context and the corresponding relative effectiveness of the internal tool-mediated learning support or the external learning support with human agency is lacking. It remains inconclusive as to what, when, and how support for learning should be designed and implemented to foster learners' extended engagement, in-game performance, and game-based disciplinary knowledge learning and transfer. In this chapter, we review prevalent support features in digital games, prior theoretical and empirical research on scaffolding and support in game-based learning, and the support design conjectures deemed effective. We then share our observations of the obstacles that learners experienced in game-based learning processes when using E-Rebuild, describe the corresponding learning support strategies and features, and report the findings from the iterative testing and refinement of these support features. Propositions for future research and the design of support for game-based learning are discussed in relation to the current project findings and prior research.

## 6.2 Prior Design and Research on Support in Game-Based Learning

### *6.2.1 Support in Digital Games*

Support features found in digital games are not necessarily designed for content learning purposes but focus on teaching novice players the flow of a game or the game mechanics (i.e., basic actions, rules, and controls) while providing an optimal level of challenge to support game engagement or flow (Chen, 2007). A common design is a non-interactive in-game tutorial that provides a static introduction of fundamentals, though they are frequently ignored by players who generally have short attention spans and are not looking to digest masses of information. To aid or motivate the tutorial processing, the designer can reward the action of attending to the tutorial with achievement points. An engaging and active substitute of the in-game tutorial is to design an assortment of training levels in which the player starts in a "noob cave" (or fail-proof) game level and then experience or learn key game controls or actions one by one via and during gameplay. Rather than providing explicit instructions, certain games (e.g., the game of Plants vs Zombies) try to use universal, basic rules of gameplay or a fairly standardized user interface, assuming the player has some familiarity with them and do not have to relearn everything. They also encourage gameplay as active self-experimentation.

To create an optimal challenge, a frequent design strategy is to progressively increase challenge or the complexity level by increasing the variables to be managed in a problem scenario (Bos, 2001). In the game SimCity, for example, the designer associates access to new game mechanics with the progression curve and gradually increases the number of changeable task parameters or rules through levels. Another exemplary support feature is an in-game "technology tree" (e.g., in the game of Civilization) that limits the players' access to advanced items or tools until they are able to master the usage of the basic mechanics.

Apart from internal game support, game community mechanisms, such as "let's play" gaming videos on YouTube and community support via forums, conferences, and blogs, have provided both learning and socioemotional support by peers and developers. Prior research (e.g., Ho & Huang, 2009; Steinkuehler, 2006) on online game communities has reported that online communities for gamers have reinforced not only participatory culture but also transactional and social learning processes.

Because the game designers' focus is on preventing frustration and reinforcing enjoyment more than the effectiveness of learning embedded domain-specific knowledge, the scaffolding or support approaches in digital games may have the potential to act as learning barriers (Sun, Wang, & Chan, 2011). For example, instant feedback and demonstration scaffolding that aim to reduce frustration levels can reduce the potential for experimentation and failure-driven learning, create overreliance on system prompts without internalizing knowledge acquired from interactions with the game system, and hence undermine learning if overused. The mechanism that supports a sense of playfulness could also be in conflict with the development of purposiveness and the effort contributed to "problematizing" the game challenges with respect to academic disciplines or subjects (Reiser, 2004).

### *6.2.2 Support in Game-Based Learning*

Games are a complex learning environment in which players—especially novices—can be overwhelmed by the abundance of information to be processed, the dynamics of the game world, and the complexity of the task and consequently deterred from activities that foster learning (Ke, 2016; Wouters & Van Oostendorp, 2013). Moreover, the dynamic and instant linking between a player's action and changes in the game world may lead to trial-and-error learning in which knowledge remains intuitive without being explicated or conceptualized (Leemkuil & de Jong, 2011). Hence it is warranted to design supports in game-based learning that facilitate not only the selection and processing of relevant information but also an active organization and conceptualization of intuitive insights for substantive knowledge development.

During the past decade, increased research has examined the design features that promote game-based learning, especially learning or instructional support features. Designing supports or scaffolds to fit the game-based task properties as well as the associated control interfaces is a critical design issue (Soloway, Guzdial, & Hay, 1994). Though empirical studies examining particular game-based learning support features have increased in the past decade, research on a systematic framework of game-based learning support design is still lacking. The literature has, however, shed light on a design framework for computer-assisted learning support in general. Wood, Bruner, and Ross (1976) initially specified scaffolding as the processes of (attention) recruitment, reduction in degrees of freedom for the problem at hand, direction maintenance, marking critical features, frustration control, and demonstration (or modeling). Building on such a perspective, Pea (2004) and Reiser (2004) observed that scaffolding serves three main major purposes: (a) channeling and focusing (or task structuring), such as reducing the degrees of freedom for the task at hand by providing constraints that increase the likelihood of a learner's effective action and recruiting and focusing learners' attention by marking relevant task features in what is otherwise a complex stimulus field; (b) modeling, such as demonstrating a solution to the task, with or without human agency (e.g., modeling by software features or a socially interactive other); and (c) content problematizing—tools or features that can shape a learner's performance and understanding of the task in terms of key disciplinary content and strategies while problematizing the disciplinary content with the task at hand. Quintana and his colleagues (2004) then tried defining a scaffolding design framework for computer-assisted scientific learning environments via a theoretical review and a synthetic analysis of exemplary courseware. They classified a list of design heuristics and techniques of scaffolding based on the basic problem-solving processes to facilitate, such as sensemaking (or problem and content representation), process management (or task structuring along with modeling), and articulation and reflection (for content problematizing). These earlier frameworks of scaffolding, along with the previous empirical studies on specific game-based learning support features, have all informed our design of learning support features in E-Rebuild.

Wouters and Van Oostendorp (2013) conducted a meta-analytic review of 29 studies on the effects of instructional support in game-based learning. They reported that players benefit from instructional support for knowledge ($d = 0.33$, $I < 0.001$), skills ($d = 0.62$, $I < 0.001$), and in-game performance ($d = 0.19$, $p < 0.001$). Support features that facilitate learners in attending to and selecting relevant information ($d = 0.46$, $p < 0.001$) are more effective than the ones that stimulate organizing and integrating new information ($d = 0.14$, $p < 0.01$). Especially, modeling (or explication of the problem-solving procedure), multimodality, personalization, and feedback are effective techniques to support learners in selecting relevant information. Their analysis indicated that the most effective instructional support for information organization and integration is reflection ($d = 0.29$), in which learners are explicitly asked to think about their actions or decisions. Instructional support that less explicitly stimulates the organization and integration of information, such as narrative elements and collaboration, seems to be less effective ($d = 0.11$ and $d = 0.14$, respectively). They also reported that the effectiveness of instructional support in game-based learning was significant for elementary school and college/university students ($d = 0.19$, $p < 0.05$; $d = 0.41$, $p < 0.001$, respectively), but not significant for middle or high school students.

The recent work of Kao, Chiang, and Sun (2017) on scaffolding in game-based learning environments reported that marking critical features facilitated conceptual knowledge acquisition better than demonstration, and the two scaffolding types facilitated different dimensions (sensitivity and flexibility) of design creativity. Mayer and Johnson (2010a, b) reported that people who played the circuit game learned faster and were better able to transfer to new problems if they received in-game guidance in the form of *non-interruptive* self-explanation (i.e., selecting a reason for each action) or feedback (i.e., being shown the reason for the correct action). They concluded that the educational impact of a game can be substantially improved by incorporating support features aimed at guiding the learner's cognitive processing during playing. Their conclusion was supported and extended by a later study by O'Neil et al. (2014) who found that self-explanation prompts aimed at helping game-based learners make connections between game variables and disciplinary concepts (or content problematizing) are especially effective.

Other studies have similarly examined external supports for game-based learning. For example, Barzilai and Blau (2014) found that conceptual external scaffolds provided before gameplay led to better problem-solving (in comparison with the play-only condition or external scaffolds provided after gameplay) but lowered perceived learning. Presenting external scaffolds may have conceptualized learners' understandings of the game by connecting them to disciplinary knowledge, but its effectiveness is moderated by the timing of the scaffolding. Tsai et al. (2013) examined both teacher-initiated content presentation before gameplay and student-controlled in-game question prompts as game-based learning scaffolds. They reported that scaffolding before and during gameplay promoted knowledge test performance better than scaffolding only during gameplay and non-scaffolding conditions. Promisingly, the embedding of background content objects or question prompts did not influence students' perceptions of their gaming experiences. Chen and Law (2016) examined and compared two types of external supports for game-based learning: nonadaptive question prompts provided after gameplay (called hard scaffolds) and peer discussions during collaborative gameplay (called soft or dynamic scaffolds). They found a significant positive effect of both external supports on learning performance but a negative impact on motivation (competence, autonomy, and interest). They also found that after-gameplay question prompts can reinforce the effectiveness of collaboration for game-based learning.

In summary, the previous study findings suggest that the content of the scaffolds, as well as the timing of their provision, should be carefully designed according to the game features to achieve specific instructional purposes. Supporting the arguments of Wood et al. (1976) and Pea (2004), in-game learning scaffolds that highlight channeling, focusing, and content problematizing while being non-interruptive are found effective. External scaffolds, such as collaboration and question prompts aimed to explicate knowledge development, can be effective, but their effectiveness will be moderated by the timing of the scaffolds.

## 6.3 Design Conjectures and Observed Challenges in Game-Based Learning

The design of game-based learning in E-Rebuild, as described in the previous chapters, assumes that core game actions will necessitate transactional and problem-based learning in which players interact with dynamically represented elements of a building-themed math problem, select and coordinate related information embodied in game objects, plan and experiment with the problem-solving actions in an interactive game world, and comprehend the task (with its variables and relationship structure) in terms of key disciplinary content and strategies, thus engaging in mathematical conceptualization and problem-solving. These design conjectures imply multiple expectations on the game-based learning processes—attentiveness, purposiveness, and need for cognition of a problem-based or discovery learner, an acquired motive or sense of legitimacy toward "content problematizing," as well as a prerequisite resource base for performing entry-level tasks (e.g., the basic math content knowledge and skills for building-themed problem-solving).

Yet heterogeneity in the school student group and the complex nature of game-based problem-solving induce observed participation and outcome variability in which not all participants respond to game-based learning tasks in an expected or favorable way. In particular, we found that many students lack training in comprehending and representing the mathematical relationships in a multistep context problem, need help to connect and structure distributed task information embodied in game objects and game actions, and do not automatically engage in the cognitive or affective processes of game-based learning. Some of them also lack entry-level conceptual knowledge or general understanding of design problem-solving.

In the initial prototype of E-Rebuild, we tried presenting a multistep, building-themed math problem in its lifelike form via a single game level. A mission description (or design problem statement) in the opening task panel worked as an overarching task narrative. Designed as an open-ended learning environment, the game world was a simulated natural landscape in which building items (or materials), a potential construction site, and the structure to be built (with its criterion properties) were situated but not explicitly denoted. Relevant cueing was presented within the opening task narrative (e.g., "those shipping containers should be of help") or as learner-controlled, displayable visual aids (e.g., a "historical view" portrays the structure to be rebuilt in the pre-quake landscape, via a 2D slideshow as well as a 3D emulation of the pre-quake structure and landscape). These design efforts were intended to highlight aspects of mystery and puzzle in gameplay and game-based, realistic math problem-solving.

Frequently, however, participants were not fully processing or digesting a written task narrative at the beginning of gameplay, even when the narrative was concise and evocative. They appeared to treat it as an affective plot opening rather than a mental riddle containing the critical task message and hence lacked attentiveness to delineate the embedded problem goal and variable information. The open-ended game world also reminded some players of commercial building games that they played (e.g., Minecraft), who then intuitively transferred the related gaming actions or strategies (e.g., exploring the game world freely and building items at one's own will and standard) to the current game. As observed, they were often wandering around the 3D landscape, clicking around, and picking up collectible objects randomly. They then assembled the collected items casually, without an understanding of the building goal/problem and the related design criteria. They became puzzled upon receiving the level-failed message and asked, "What are we supposed to do?" It was only after multiple failed trials would they realize that their old gaming habits did not work and hence show more attentiveness in reading the task narrative and other in-game cues. Other learning habits or preferences, such as the need for explicit, step-by-step procedural guidance along with the lack of appreciation of independent puzzle solving (or a low need for cognition), made them easily frustrated from game bottlenecks and frequently asking for instant help from peers or a facilitator, "What should I do now?" Instead of looking to maximize "hard fun," these players wanted to pass the level and end the problem-solving experience as soon as possible.

We also observed that players tended to lack persistent effort in task structuring (i.e., mapping sub-goals and planning steps beforehand). For example, we expected that a player would proceed with a logical process of site surveying, planning the structure to be built (in terms of the size, shape, and position), collecting/trading items needed, building as designed, and allocating inhabitants to the compartments of the structure. Yet most players were involved in intuitive, trial-and-error game actions that lacked system thinking; instead, building instantly with only items at hand while searching more items as needed, building a random structure, finding it impossible to allocate all inhabitants, rearranging/rebuilding the structure, reallocation (potentially with repeated mistakes), and so on. This unsystematic problem-solving process, to some extent, generated failure-driven, reflective understanding about the presence of a mathematical relationship among task variables. It was, however, non-mathematical and thus made it difficult for the players to complete sufficient levels within a class session. To assist these intuitive-thinking players, we provided a short list of sub-tasks (or marking the task structure) on the task panel. This design feature did significantly improve the players' in-game performance (e.g., the number of levels completed within a session) but reduced the opportunity for the participants to practice representation for multistep problem-solving (Ke, 2007). This finding is consistent with prior research which found the big challenge for designing game-based learning support is to find a balance between supportive tool availability and encouraging learners to engage in discovery learning and accept some level of frustration from game bottlenecks (Sun et al., 2011; Yelland & Masters, 2007).

E-Rebuild learners also experienced a learning curve in coordinating information distributed across objects and actions in the 3D virtual world. Situating a mathematical problem in a 3D world, representing related problem variables as interactive objects or action feedbacks that are distributed across game space and time, and making one actively search and connect (rather than being provided with) the embedded information were generally novel practices to middle-school students. In the initial E-Rebuild gaming sessions, we commonly observed that participants lacked purposiveness in storing and using information obtained during the previous game object or action to guide their next move. Even when sub-tasks were marked explicitly, participants tended to treat them as separate assignments rather than part of a holistic problem. Based on think-aloud protocols and interviews, participants generally lacked a solid understanding of the systematic nature of mathematics—the need to work on a higher logical plane in problem-solving situations—and understanding which and why mathematical relationships and ideas are useful in a particular context for problem-solving.

## 6.4 Pros and Cons of Learning Support Design Strategies

Driven by both the literature on game-based learning support and the observed learning challenges in E-Rebuild, we experimented with multiple learning support design strategies: (a) channeling learners' attention toward the final target task by displaying sub-tasks in structure and constraining the space exploration to maintain directedness of the learner's activity toward task achievement; (b) presenting/sequencing game tasks (or levels) with gradually increased degrees of freedom, by reducing the numbers of variables in the task structure involved in the initial problem scenarios; (c) modeling or scaffolding the representation of mathematical relationships in a task with interactive step-by-step prompts, an in-game scratch pad, multimodal cues, and feedback; and (d) externally supporting content problematizing by encouraging learning-constructive game talk among peers and external help as needed from a facilitator or teacher. The pros and cons of these learning support design strategies, with the illustration of our design experiment findings, are described in the following section.



### *6.4.1 Structuring and Sequencing of Game Tasks*

To assist players in mapping and systematically planning problem-solving steps, we have experimented with alternative ways of chunking and structuring a game task. One method involves chunking and sequencing *sub-goals* (or componential steps) of a composite task, while another involves chunking and then gradually increasing the set of influencing *variables* of the problem/task.

**Sub-Goal Chunking and Structuring** In our earlier prototype, we tried the first chunking/structuring strategy by evaluating each sub-goal as a componential task, sequencing them linearly as a succession of tasks, and showing only the "instant" sub-goals with a task completion progress bar (Fig. 6.1a). The next sub-goal or task (e.g., allocation) was locked until the previous one (e.g., building) was completed. This design arrangement highlighted a "step-by-step" guidance on task structuring.

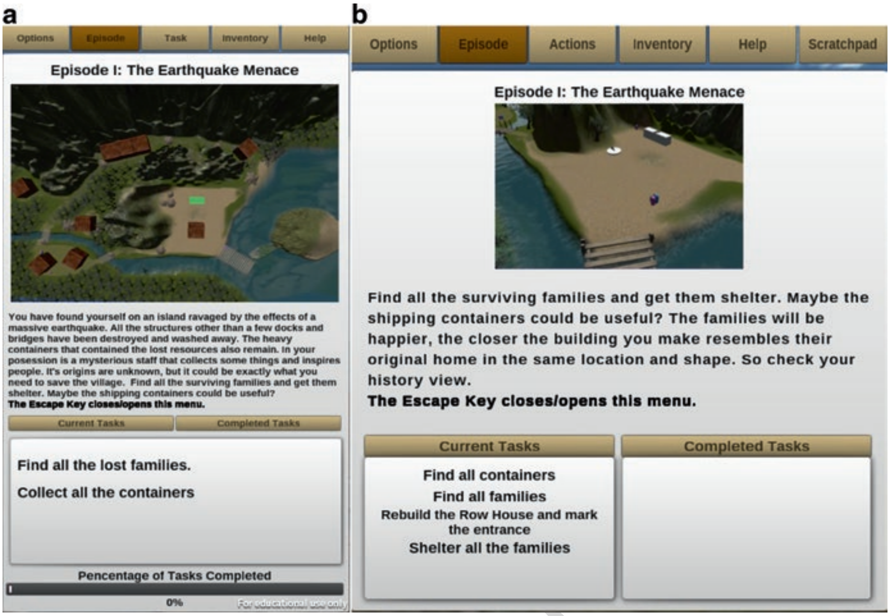



**Fig. 6.1** (**a-b**) Marking and sequencing of sub-goals

Such an arrangement has obviously fostered in-game task performance and on-task time, in comparison with the initial design that presented a multistep task as it is. Yet we also observed that the explicit and linear sub-goal structuring reduced the opportunity for the participants to proactively reflect on and refine their understanding of mathematical relationships underlying the task structuring. For example, in the episode depicted in Fig. 6.1, the building problem (using multiple containers to build a shelter resembling the pre-quake home and allocating all surviving families to containers) includes two puzzles: (1) the number of shipping containers needed and (2) the way the structure should be composed. When interacting with the initial version, participants were frequently found transferring between the two steps of “rebuilding” and “sheltering all families” to self-check and refine the answer to the first puzzle. Yet under the linear and chunked task structure, both puzzles had to be solved at the building step, and the participants lost meaningful action feedback (e.g., whether all families get sheltered). Hence more participants started trial-and-error gameplay: building with all containers, letting the computer or game check the built structure, and reducing one container at each new trial until they passed this step.

In a later prototype, we presented all sub-goals of the composite game task as a to-do list (Fig. 6.1b), with which the player can check off each completed sub-task at a nonlinear sequence. All sub-goals or componential tasks are parallel and not prerequisite of each other. The flexible sub-goal list helped to channel the players' attention while allowing them to navigate and convert between sub-goals (or tasks).

As the gaming behavior analysis indicated, the nonlinear sub-goal chunking, in comparison with the linear one, was associated with more enactments of content learning engagement (e.g., information processing, calculation, knowledge application) and generic cognitive engagement (e.g., planning, evaluation, refining). However, providing the players with a specified sub-goal list has reduced the necessity for learners to proactively construct and experiment with personally meaningful representations of a multistep math context problem. They thus missed the opportunity to practice problem identification with task structuring, a critical element for realistic math problem-solving.

**Variables Chunking and Escalation** To enable an exploration or experience of the systematic nature of mathematical relationships in a problem while scaffold task structuring, we tried examining the number or structure of problem variables as an additional salient entity for game level organization and sequencing. Specifically, we designed and sequenced game tasks with a gradually increasing number of influencing variables (or degrees of freedom) involved in the underlying mathematical relationships. In a classroom building level of the School episode (Fig. 6.2a–b), for example, the problem involves multiple variables: unit classroom/container space, unit space need of each student of each subject, the total space/area needed, and the positioning (and distance) of classrooms. The logged failed attempts, the frequency of help requested, and the observed frustration level of participants were all higher than expected in the original version (Fig. 6.2a). We therefore chunked the original level into an easier version (Fig. 6.2b) where the positioning/distance variable was temporarily removed. In the next level, a more composite version of the task was then presented with the full set of the variables. The revision increased participants' task performance and content-engaging actions.


**Fig. 6.2** (**a**, **b**) Chunking and sequencing by task variables

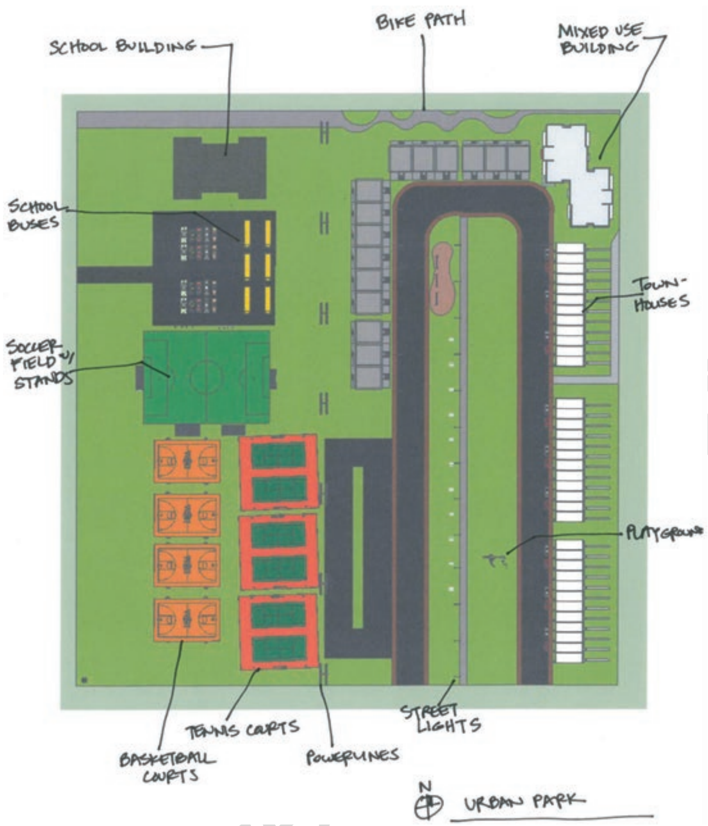



**Fig. 6.3** The plan view of the school set design

**Constraining Game Space and Highlighting Information Points of Interest** We additionally found that constraining the game space helped to reduce the task-irrelevant locale exploration acts and channel participants' attention toward problem information processing and selection. Take the aforementioned School episode as an example; the earlier version presented a full replication of an urban school setting (Fig. 6.3), designed by the architect consultant on the team. Proceeding from the previous Desert episode to this lifelike School episode, participants (at a local school district in Florida) all demonstrated a high level of excitement with the richness and attractiveness of the 3D game world. They became immersed in the environmental story portrayed by the game space: navigating and checking every structure and background object of the set and asking the facilitator whether they could drive a school bus or how to enter a locked townhouse. They spent more time exploring the task-irrelevant game space than fully processing the task narrative and related information objects. Due to this observation and the need to downsize the game file to run on the local school infrastructure, we reduced the magnitude of the school set and background structures/objects. To better focus the players' attention

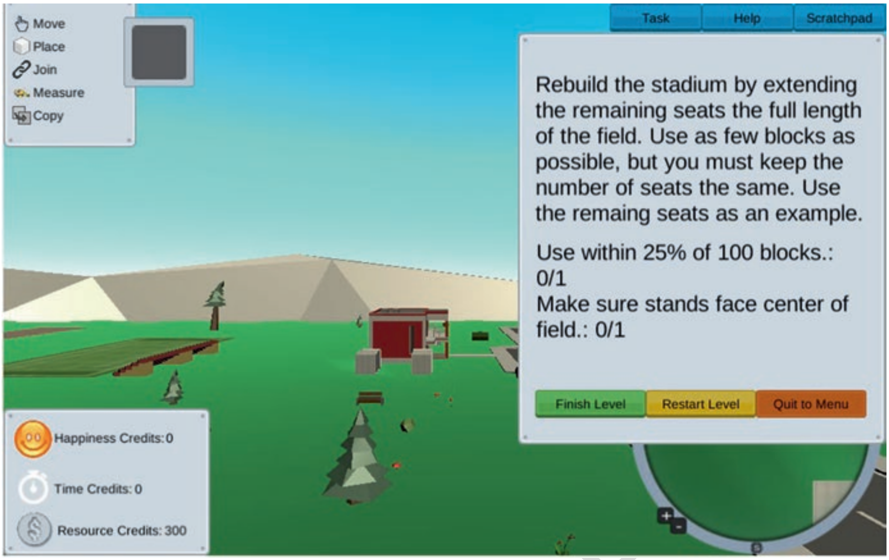



**Fig. 6.4** The school stadium level—starting point

on the salient problem variables (or the embodied game objects), we purposefully made the *information point of interest*—the object that is critical for the problem identification—as the starting point of gameplay at each level. For instance, in a school stadium building level (Fig. 6.4), participants had to analyze the structure of the stadium's bench seating and find a way to build it in an efficient way. The problem requires the player to decompose and compose geometric shapes (e.g., a trapezoidal prism as the base and a rectangular prism as the seat) and join and copy/paste small cuboids of standard or varied dimensions (e.g., bricks) to construct the base and seat of the stadium bench. This task, as observed, was novel to our middle-school participants who struggled in analyzing the composition of the structure, usually spending more than 30 minutes in a single attempt or trial, and frequently requesting hands-on help with the building process. Specifically, they did not fully inspect the bench to notice its hollow rear. To correct this misapprehension, we set an isometric view of the bench's rear (instead of the elevation view of its front side, as in the earlier version) as the starting point of the level. We also colored the base and seat section of the bench differently to highlight its geometric composition. All of these design revisions with the game space have clearly reduced the off-task time and actions by the participants.

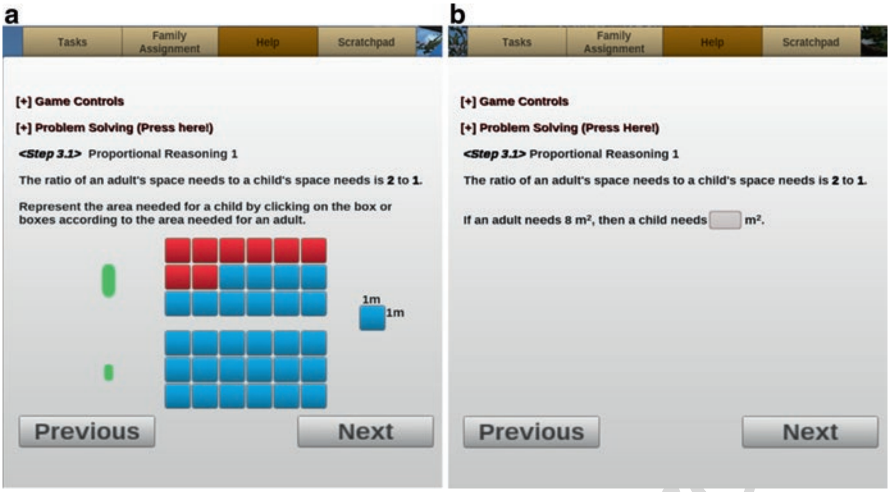



**Fig. 6.5** (**a**, **b**) Scaffolds of mathematical relationship representation in iconic and symbolic formats

### *6.4.2 In-Game Scaffolding of Mathematical Relationship Representation*

To scaffold players' comprehension and representation of the mathematical relationships in a game task, we tried adding step-by-step, interactive prompts, presented in both pictorial (or iconic) and symbolic formats, in the Help panel (see Fig. 6.5). An empirical investigation of this scaffolding feature (Lee, 2016; Lee & Ke, 2016) found a significant and positive impact of using this representation scaffold, especially in symbolic form, on learners' conceptual and procedural mathematics knowledge development via gameplay. Yet the infield observations indicated that players would not necessarily attend to or process the mathematical scaffolds unless they were associated with explicit game rewards.

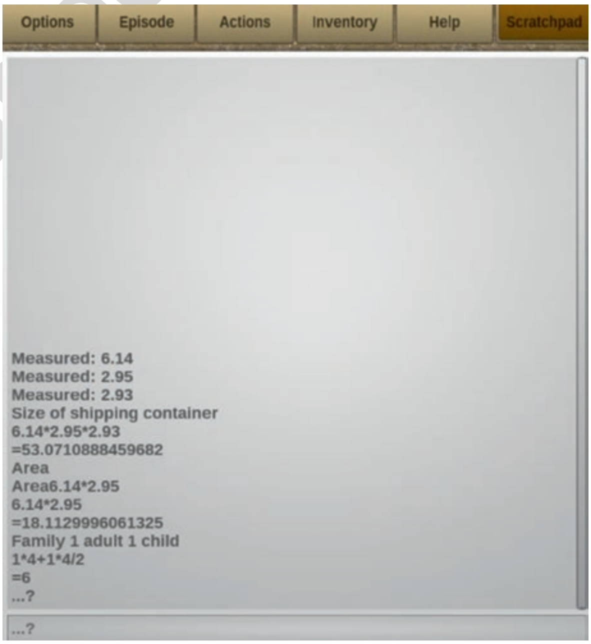
Tina got stuck on the numerical expression and calculation of a family's space need and started to use a trial-and-error strategy with the prompt—entering random values to the text area until she guessed the right one. The scaffolding window presented instant feedback on every entry (e.g., reddening the wrong entry without proceeding to the next screen), aiding the trial-and-error practice. Proceeding to the next prompt, Tina kept guessing on a related math variable—the total space needed. It appeared that she did not understand or remember the ratio statement and the variable of family space processed/calculated during the previous step. Her neighbor asked, "How did you figure out what (number) goes here (a variable in the equation)?" She answered, "I was just typing numbers."

As this observation shows, certain participants failed to associate the interactive scaffolds on numerical expressions with the game task at hand and deemed these scaffolds as boring hindrances during gameplay. In contrast, other participants, driven by multiple failed trials of the game task, were cognitively engaged in interacting with the scaffolds.

Jeremy got stuck in the family allocation task and failed multiple times. He started to check the help panel. It appeared that this was his first time reading the scaffolding section seriously. He completed the first three ratio prompts smoothly. He entered correct variable values in the equation for calculating the space needed for a 1-adult-2-child family, but did not calculate the total correctly until the third trial, indicating a lack of competency in interpreting and calculating the mathematical expression. He got stuck with the equation for a 2-adult-1-child family in the next step; he entered wrong values for the space needs of each adult and child, lacking a solid understanding of the math concept of unit. He went back to the previous step and reviewed the equation of the 1-adult-2-child family. After fully comprehending that mathematical expression, he then reworked on the equation for the 2-adult-1-child family. This time he entered correct values for both the unit and total space needs.

In the above example, the participant had developed a better understanding of the unit concept and the mathematical equation representing the space needs of varied families. As exemplified, in-game scaffolds assisted participants' encoding of the math problem using mathematical expressions or notations, but only when they were processed mindfully. Therefore, it is important to design the in-game scaffold of mathematical representation in a way that the players will perceive the scaffold as a sensible investment of cognitive effort and an essential support for their gameplay or game-based problem-solving process.

**Fig. 6.6** An in-game scratch pad



**In-Game Scratch Pad** In E-Rebuild, we designed an in-game scratch pad (Fig. 6.6) as a virtual calculator and a virtual worksheet with which the player can write, plan, and record their problem-solving steps and calculation processes. Specifically, when conducting a site survey using the measurement tool, the player could conveniently select and record measurements to the scratch pad for quick numerical calculations. The infield testing indicated that players frequently used it as a calculator and a notepad for measurement recording, yet few used it to scribe or plan problem-solving steps. A critical reason for this finding is that electronically typing mathematical expressions and equations is effortful for middle-school students. In addition, the players could not map or encode the mathematical relationships via freehand diagrams or visuals, on the scratch pad. Hence instead of using the virtual scratch pad, the players preferred to use the offline paper worksheet to aid their problem-solving and calculation processes. However, using an offline worksheet could be interruptive to the players' gameplay flow and not quite compatible with the desk space that was already packed with the computer, keyboard, and mouse. Consequently, participants tended to either work on a small sheet of paper in between the equipment or choose to bypass the problem-solving scribing or mapping processes. Creating a user-friendly, efficient, and multimodal in-game scribing tool is a continuing design challenge in E-Rebuild.

**Multimodal Cues and Feedback** To recruit and maintain the players' attention on the salient objects and features in the task structure and facilitate the reflection and purposive refining of problem-solving actions, we designed in-game scaffolds also as tooltips, action-specific feedback, in-game tools, and end-of-level badges. These in-game scaffolds are multimodal, in line with the game mechanics and game world, and presented in response to a game act or at the end of a game level.

In the original prototype of E-Rebuild, we tried putting all salient problem information, including core variables and their features, into the task narrative being portrayed on the Episode panel when one entered a game level and ever-present as a background information object. However, we found that on average, participants spent less than 1 minute reading the task narrative, with some simply skipping it. We then tried presenting salient information as a tooltip associated with each game object or element. The information appears when an anchor was positioned over the related object, as shown in Fig. 6.7. As observed, interacting with diverse information objects in the game world had involved participants in an in situ and active investigation of the related problem variables and helped them to comprehend the problem through hands-on discoveries.

During the design experiments, we found that action-specific cues, in comparison with ever-present cues, are better received and processed. For example, in the trading action, we used to present items' prices via a background bulletin board that replicates the format of a math ratio table (Fig. 6.8a). We observed that middle-school participants frequently ignored the board in the store house. They would make a random estimate of an item's price, make an unreasonably high offer, purchase certain items, run out of resource credits during the task, and thus needed to


**Fig. 6.7** Salient variable information presented as a tooltip

retry the task. Only after multiple failed attempts in the trading action would they be willing to carefully read the price bulletin board. In response, we added a tooltip presentation of building items' prices in the inventory, which has reduced trial-and-error processes and promoted numerical calculation behaviors by participants during the training action.

A similar pattern was also observed with the action-specific feedback. For the allocation action in E-Rebuild, we designed an item-allocating panel (Fig. 6.8b). During the infield testing, participants complained that the panel was blocking the game world, and they could not see whether and what item (e.g., a specific type of family) was added or not. Correspondingly, they were found randomly clicking on the adding or reducing buttons without purposive planning or mathematical reasoning. As a result, we changed the allocating interface to enable action-specific, immediate visual feedback: a player can drag items from the inventory to the target space, with the items either appearing in the space (if applicable) or reverting back to the inventory (in a spaced-out situation). We also added a reddened alert at the bottom of the screen cueing them about the reason for each unfitting occasion. The provision of action-specific, intuitive feedback has again fostered participants' mathematical reasoning and calculation behaviors during the game action.

To activate students' reflection on their actions, we tried to present written, informative feedback in a game performance summary at the end of each game level. But again, few participants carefully read the summary; most only skimmed through it before proceeding to the next game level. Although participants did attend to the three game credits presented on the left bottom corner of the screen, many of them did not fully comprehend the relationship between each credit and their specific gaming behaviors. To encourage action-based reflective learning and mathematical reasoning during gameplay, we have instead designed and presented a badge system on the post-level summary (Fig. 6.9). Each badge is designed and presented to

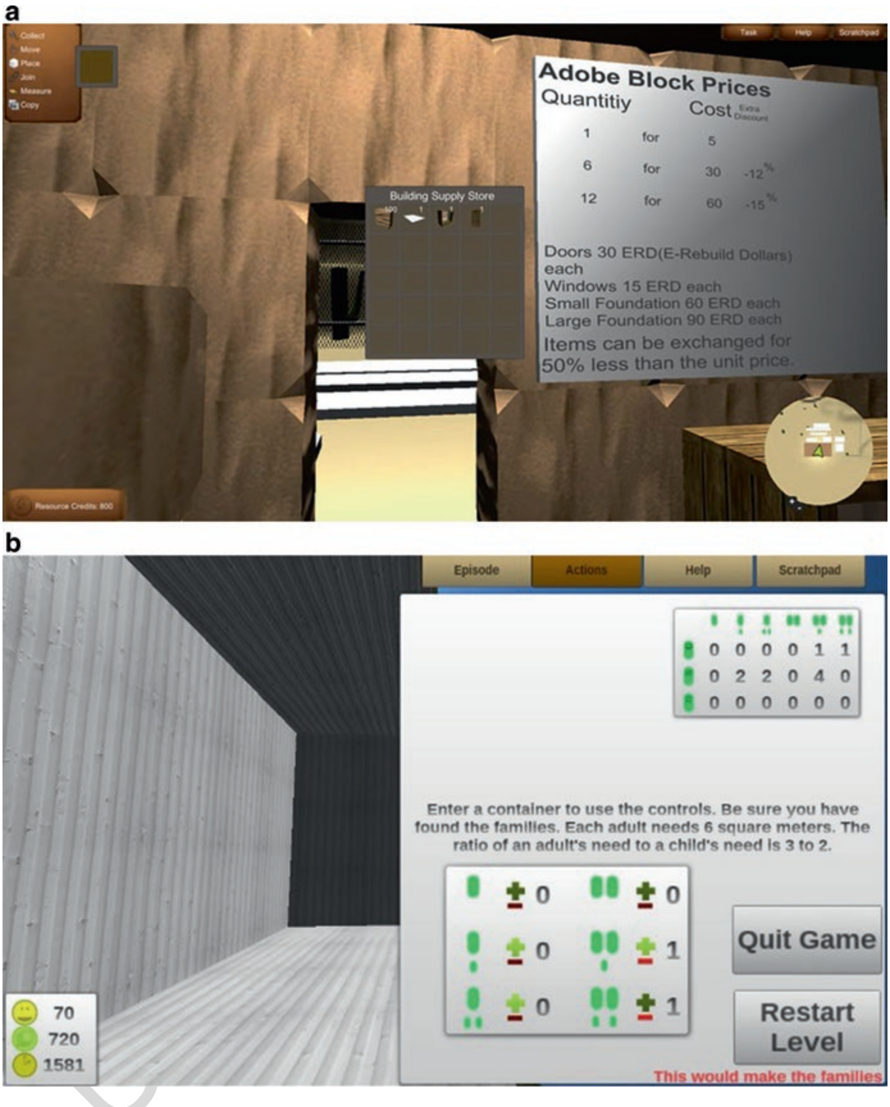



**Fig. 6.8** (**a**, **b**) Price bulletin board for the training action and the item-allocating panel

encourage a player to improve the efficiency and accuracy in their game-based problem-solving strategies and solutions and hence motivate a purposive usage of mathematical reasoning and knowledge in the future game levels.

*2D/3D Visuals for Alternative Processing and Comprehension* An example demonstrating the benefit of multimodal in-game scaffolds for problem representation was the pairing between a 2D visual sketch and a 3D model of the target architectural structure in E-Rebuild (Fig. 6.10). The former was presented as a slideshow,

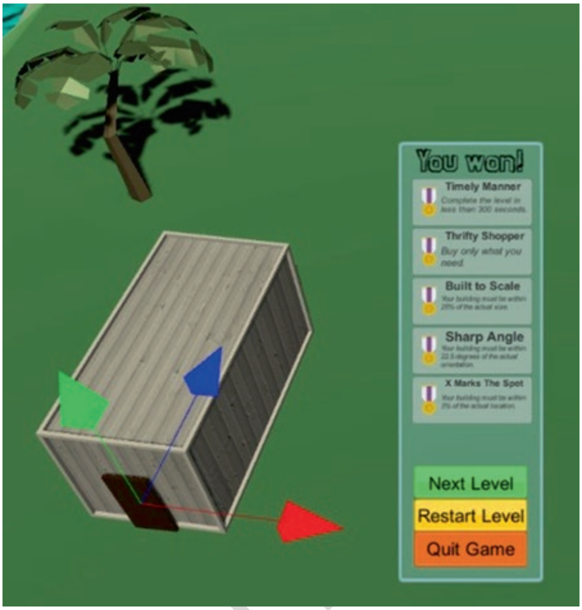



**Fig. 6.9** Post-level game performance badges

while the latter was presented as a historical view of the structure and construction site with which the player could actively inspect and survey. When interviewed, participants generally reported that they referred to both forms of the visual-spatial representation during gameplay, which was confirmed by the infield observation of their gaming behaviors. During the building action, participants frequently shifted between reviewing the static, visual depiction (with numerical marking) of the target structure and exploring/measuring the structure model situated in the simulated construction site. This pattern confirmed our speculation that such a multimodal representation scaffold enabled learners to comprehend static visuals while interacting with a maneuverable object or model, thus sufficing both visual and kinesthetic ways of information processing.

In a recent study on the patterns of scaffolding usage of participants of E-Rebuild (Dai, Ke, & Pan, 2017), we found that the help panel was the most frequently used in-game scaffold and was used for the longest time, followed by tooltips, prompts, and summary screen. However, the time spent on these in-game scaffolds was generally short, ranging from 6.85 to 44.65 s per 45-min gaming session. The frequency of using in-game scaffolds has a positive correlation ($r = 0.20$, $p < 0.05$) with the frequency of learning engagement.


**Fig. 6.10** 2D floorplan slideshow and 3D historical view of the structure

### *6.4.3 External Scaffolding*

In addition to the in-game scaffolding, we also encouraged learning-constructive game talk among peers and external help as needed from a facilitator during participants' gaming sessions. Even though E-Rebuild was developed as a single-player game, participants voluntarily partnered up with their neighbors during gameplay, updating or showing off their gaming progress with each other, sharing tips or strategies, or venting frustration. Though the game talk was not fully mathematics relevant, it acted as an external support for game task engagement. Via the game talk, student participants frequently sought help and affective support from each other. They also relied on the external scaffolding offered by a trained facilitator. The facilitator's scaffolding in the E-Rebuild program included question-answering on the game mechanics, modeling of the 3D object maneuvering procedure, cueing on the information to be processed or the potential way to unblocking a bottleneck, and prompting for action-based reflective thinking. Notably, we found that external scaffolding by the facilitator was especially beneficial for the participants who were underachieving in mathematics. There was a positive association between the facilitator scaffolding usage and these students' post-gaming math knowledge test performance. Yet these students, in comparison with their peers, were significantly more passive in seeking external help. We thus requested the facilitators to provide proactive and recurrent scaffolding to the underachieving students, though it was difficult in cases when multiple students required help.

Our study on the scaffolding usage in E-Rebuild (Dai, Ke, & Pan, 2017) indicated that student participants generally sought a similar number of human facilitator scaffolds and in-game scaffolds, but they spent much longer time with human facilitators. In addition, participants received much more scaffolding, in both frequency and time spent, from adult facilitators than from their peers. There was a significant correlation between facilitator scaffolding and learner's engagement behaviors ($r = 0.26$, $p < 0.05$).

## 6.5 Conclusive Design Insights on Game-Based Learning Support

Our design and research findings in E-Rebuild have highlighted and confirmed a salient claim in the literature on computer-assisted learning support—*only when a support is context-aware and intrinsically integrated in the technical environment will the support be effective*. In game-based learning, a support should not only be context- or environment-coherent but also action specific. Game-based learners have a short attention span for textual information processing in a dynamic game world and are occupied with in-game problem-solving. Consequently, they tend to interact with learning supports when they are game action- and object-associated, perceived as a legitimate investment (e.g., a worthy solution to block repetitive failures), and presented in a multimodal and non-interruptive way (i.e., not constituting extra information-processing load).

Confirming the literature on game-based learning support (Wouters & Van Oostendorp, 2013; Mayer & Johnson, 2010), the current project findings suggest that learning supports that scaffold mathematical relationships (or task structuring) are beneficial to learners' in-game task performance and learning outcomes. Specifically, chunking and sequencing sub-goals as well as gradually increasing componential variables in the game tasks help to channel the players' attention and effort toward the overarching task goal and a systematic problem-solving process. However, it remains a design challenge to create an in-game task-structuring tool that enables mathematical diagraming or freehand scribing or a tool that bridges action- and visualization-based qualitative insights to mathematical expressions of the variables with their analytical relationships in an architectural building problem.

In the E-Rebuild project, we have found that internal and external scaffolding can complement each other to create a coherent learning support system. Proactive and individualized external support particularly assists underachieving students. Yet individualized learning support via a trained facilitator is demanding in the school settings. A potential solution and future research topic of the E-Rebuild project is to provide in-game adaptive learning support that is driven by the real-time assessment of the cognitive and affective states of the learners during gameplay. For example, the game data-driven assessment of a learner's math competency and affective states can drive an adaptive selection and sequencing of game levels that supports an optimal learning path and level of challenge. Within each game level, the real-time tracking of the learner's in-game task performance and engagement state will then trigger multimodal support features that are adaptive in the content (e.g., associated with the action at hand or the object being interacted with), timing (e.g., when a threshold value of failed trials or the bottleneck state is reached), and format (e.g., modeling or prompting for a partial solution). These adaptive learning support strategies can augment the current in-game scaffolding features and balance learner autonomy in selecting the preferred support mechanism.

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# Author Queries

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| Queries | Details Required | Author's Response |
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| AU1 | Please check sentence starting "Yet most players…" for completeness. | |
| AU2 | Reference "Johnson & Mayer (2010)" was not cited anywhere in the text. Please provide in text citation or delete the reference from the reference list. | |
| AU3 | References "Ke, 2016, 2007; Mayer and Johnson (2010a, b)" are given in the text buit not provided in the reference list. Please provide. | |

# Chapter 7
# An Evolving Design Framework for Game-Based Learning Platforms

**Abstract** In this concluding chapter, we discern and discuss an evolving, experiential design framework for game-based learning platforms, by synthesizing the salient design problem-solving events, experiences, and solution-exploration findings reported in the previous chapters. It is not aimed to be prescriptive or exhaustive, but acts as a starting point for specifying the structuring and important concepts of the interdisciplinary design of game-based learning. Results of our phenomenological inquiry assert that game design problem-solving is mainly about problem structuring or transforming an indeterministic problem space to partially limited. The structuring of the interdisciplinary design of game-based learning platforms consists of three norms: (a) transformation of the design goals into functional specifications of the design artifact, (b) coevolution of the problem and solution spaces and exploration and syntheses of partial solution of the subproblems, and (c) use of a common symbol (or representation) system to communicate and focus information while augmenting collective memory and processing.



## 7.1 Introduction



Design is innately an ill-structured problem and a phenomenon difficult to model. Design studies on ill-structured design problem-solving, such as those in the fields of architecture and engineering, were mainly aimed to discern a generic design model that is versatile in describing the invariant nature of design problem-solving across the fields (e.g., Brown & Chandrasekaran, 2014; Dorst & Cross, 2001). These generic design models shed light on our examination and understanding of the game design process. But they come short of suggesting tangible solutions or explaining applied reasoning processes for educational game design.

In this concluding chapter, we discern and discuss an evolving, experiential design framework for game-based learning platforms, by synthesizing the salient design problem-solving events, experiences, and solution-exploration findings reported in the previous chapters. This framework is aimed to extend and enrich previous generic design models with discipline-specific and functional design



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knowledge emerged from our phenomenological inquiry. It is not aimed to be prescriptive or exhaustive but acts as a starting point for specifying the structuring and important concepts of the interdisciplinary design of game-based learning.

## 7.2 Structuring of the Game Design Spaces

Game design is characterized by an open-ended or unspecified goal state and an extensive, indeterminate design problem space—in which the transition states (or paths) between the design input and output (or goal) states can be unlimited and their connections are unknown. Results of our phenomenological inquiry assert that game design problem-solving is mainly about problem structuring (Newell & Simon, 1972; Simon, 1973) or transforming an indeterministic problem space to partially limited. The structuring of the interdisciplinary design of game-based learning platforms consists of three norms: (a) transformation of the design goals into functional specifications of the design artifact; (b) coevolution of the problem and solution spaces, including defining the space constraints, decomposing the problem into interconnected components, and exploration and syntheses of partial solution of the subproblems; and (c) use of a common symbol (or representation) system to communicate and focus information while augmenting collective memory and processing.

### *7.2.1 Transformation of Interdisciplinary Design Goals into Functional Specifications*

To formulate the design problem, we have tried to explicate, synthesize, and transform the design goals into functional specifications of the design product. Because game design is the experience design, the problem formulation investigation is hence driven by a basic question: What learning-gaming experience will we design? Specifically, a design team has to address the following sequence of questions to specify the *mechanics nature* of the game-based learning experience:

- What composes a salient problem-solving or epistemic practice in the disciplines (e.g., mathematics and architecture)?
- What desirable aesthetic experiences—emotional and cognitive responses evoked in the player—are associated with such a practice?
- What game objectives, actions, rules or constraints, and environmental storytelling will promote the relevant disciplinary practices and aesthetic experiences?
- Is designing such an experience applicable considering the technical and pragmatic constraints (e.g., time, budget, resources at hand, and the future implementation setting)?

The above questions have helped to bring to bear interdisciplinary team members' personal and disciplinary knowledge on the design problem formulation and channel their attention and discussion on the core game mechanics and game world design.

### *7.2.2 Coevolution of the Design Problem and Solution Spaces*

Prior design research observes that creative design is "a matter of developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis and evaluation processes between the two notional design 'spaces'—problem space and solution space" (Dorst & Cross, 2001, p. 434). Such a design observation got confirmed by our design inquiry findings. Our design chronicle indicates that we start by exploring the problem space and identifying a partial structure (e.g., what is the core gameplay?). The partial problem structure then helps us to identify a partial structure of the solution space (e.g., a "building" action along with the 3D movement interface). We examine and use this partial structure to generate more initial ideas for the form of a design concept (such as objectives, potential challenges, and rules associated with a building action), and so extend and develop another partial structure of the solution space (e.g., actions of allocation and collection). These solution space evolutions transfer back to extend the problem space identification (e.g., how will a game task assemble and legitimize game actions in meaningful context?) and, then again, trigger the exploration of the solution space (such as the task design and chunking and the game world development). Ultimately, we create *a system of matching problem-solution pairs that are also interconnected with each other*.

It should be noted that the evolution of the system of matching problem-solution pairs for game design can be inexhaustible. To define constraints or a functional boundary to the design space, the interdisciplinary team needs to frequently review and refine the aforementioned functional specifications of the design artifact, and prioritize the design structures within the *negotiated, goal-driven boundary*.

A foundational structuring process of the game design space is to *decompose* (Alexander, 1964) the problem into subproblems that are not strictly encapsulated, with an ongoing monitoring process that looks for interconnections across them. In E-Rebuild, for example, the problem-solution space exploration is decomposed into the following interconnected facets:

- Designing game actions and rule sets that necessitate and legitimize the competency performance
- Designing an intermediary user interface to enable and motivate both functional and cognitive interactivity

- Designing and structuring game tasks, including contextual scenarios (the game world or setting), to exemplify actions in a legitimate (or meaningful) context, to scaffold learning progression, and to capture/accumulate performance evidence defined by the competency/evidence models
- Designing the game logging structure along with the development of the statistical model for stealth assessment (in this case, Bayesian network)
- Designing game-based learning support to enhance theoretical thinking and subject-problematizing opportunities

In the later stage of the design space structuring, the sub-solutions for the above subproblems are then aligned and adjusted coherently to create a synthetic design solution for the whole game design problem. For example, in the later design phase of E-Rebuild, game task development and sequencing, game logging structure design, assessment model refinement and validation, and learning support design have merged with each other so that the iterative design and refinement are proceeded with them all rather than a single facet.

### *7.2.3 Construction and Use of a Common Symbol (or Representation) System*

Using a common symbol system for design concepts among the interdisciplinary design team is imperative for a longitudinal, complicated design problem-solving process. During the E-Rebuild project, we found that a substantial amount of time during the earlier design meetings was spent in decoding, comparing, and coordinating differing symbol or representation systems of the design ideas, more than that for the design idea generation. Due to the lack of a common symbol or representation system of the design knowledge among the interdisciplinary teammates, the collaborative review and refining of the design spaces become even murkier. The use of a common "pattern" language, as we discovered, helps to communicate, filter, and focus information and augment collective memory and processing. The construction of such a design language system should actually occur as the commencement of the design problem structuring process.

## 7.3 Core Design Concepts for Game-Based Learning Platforms

Several core design concepts have emerged as the most dynamic, composite, or impelling constructs in the design spaces of game design. They embody the unique features and challenges that characterize game-based learning platforms and deserve further discussions and a deliberate examination.

### 7.3.1 Intrinsic Knowledge Integration

Prior research of game-based learning has examined and discussed the importance of integrating knowledge as an internal or intrinsic part of gameplay, such as the design exploration of endogenous fantasy (Habgood, Ainsworth, & Benford, 2005; Malone, 1981) and a recent synthesis of major approaches of integrating purposeful learning in gameplay (Ke, 2016). Actually, the nature of the knowledge is as important as the way it is integrated in or structured/enabled by gameplay. But the former receives much less design or research attention. Few game studies examine the nature of game-based knowledge to justify why its development warrants gameplay. Besides, an implicit assumption of "embedding" or "integrating" knowledge in gameplay is that the knowledge is information or static data to be represented or conveyed by multisensory game worlds.

In this project, we explore the design of game-based learning as more an experience design, with the aim to convey knowledge in interactions rather than static data. The assumption is that problem-based gameplay enables not only conceptual and procedural math knowledge but also structural understanding—understanding of the principles and conceptual relations among mathematical variables and procedures in a contextual math problem. It is also hypothesized that learners will discern new problem-solving methods from the experience, after being provided expressive ways to confront with and test the previously developed methods (e.g., trial and error) and realizing that they are restricted. These theoretical and design conjectures about learning in gameplay have surely influenced our design exploration. It is important, but beyond the scope of this book, to examine how the nature of knowledge (e.g., general schema versus domain-specific knowledge; sign-mediated theoretical thinking versus empirical thinking) will mediate the design approach of game-based learning platforms.

### 7.3.2 Meaningful Play

Although games have been frequently cited as a motivation tool for learning, design research that examines the construct and design of game-based learning motivation is still lacking (Star, Chen, & Dede, 2015). It is important for the game designers to explicate why and how different learners will find a game-based, intentional learning experience interesting (due to intrinsic motivation) or important (due to well-internalized extrinsic motivation). For example, the game-based learning designers need to resolve the conflict between the gameplay that requests considerable sense-making or cognitive interactivity and learners who may lack need for cognition—an inclination toward effortful cognitive activities.

Educational game design is to create meaningful, interactive, and challenging worlds involving the user as the conductor of his own intellectual development. In relation to this stance are three design concepts imperative for describing and designing game-based learning motivation: *autonomy with environmental regulation*, *meaning in interactivity*, and *optimal challenge*.

**Autonomy balanced with environmental regulation** Learner autonomy (e.g., user choices of the game video/audio setting, speed, and the play mode or path) is a common theme in the discussion of game engagement and usability. But we discovered that too much freedom in a game-based learning space is associated with off-task behaviors and the lack of purposiveness and mindfulness for knowledge application and acquisition during gaming. Environmental regulations of learner autonomy, such as rules and incentive structures that prioritize domain-specific methods and tools as well as a game world with a natural boundary, are imperative for game-based cognitive and learning engagement and should.



**Meaning in interactivity** Salen and Zimmerman (2005) discussed *meaningful play* as an emotional and psychological experience in a game that emerges from the relationship between player action and system outcome, when such a relationship is both *discernable* and *integrated* into the larger context of the game. This proposition is adopted and confirmed by our inquiry that the user interface should communicate the result of the game action to the player in a perceivable way while demonstrating the significance of the game action on the play experience both immediately and at a later point in the game. On the other hand, we found that the mechanism of creating *meaning in cognitive interactivity* (or psychological and intellectual participation between a participant and a system) is much more complicated than that for functional interactivity (or technical usability). For example, players may fail to discern the advantages of using domain-specific methods and tools or associate their significance with the larger context in the game. Design principles or strategies aimed to make cognitive interactivity discernable and integrated in game mechanics and settings warrant deliberation.

In the E-Rebuild, we have tried reifying values of cognitive interactivity into gameplay rules and incentive structures (e.g., a game badge system emphasizing the significance of efficiency and thriftiness as the consequence of using mathematical methods or solutions). We have also tried leveling the entry barriers in cognitive interactivity, by chunking and sequential embedding of domain-specific challenges in game levels. We design the game world and the fantasy environment as a context that justifies cognitive interactions. Specifically, discovering and interacting with objects in the game world (e.g., the actions of site surveying and item collection) are intertwined with intellectual participation (e.g., coding and calculating the mathematical properties of the site and items). Infield testing and observing the interactivity between players and the coded game system have enabled us to analyze the association between the game task/level features and the creation or reduction of the undesirable shortcut solutions (solutions without domain-specific thinking). In general, the game tasks should be designed to provide the player expressive ways to confront, test, and compare domain-specific methods or tools with generic ones.

*Optimal challenge* is the most conversed design concept or standard in the previous game studies, whereas it remains the trickiest design challenge due to the high heterogeneity in relation to prior game skills, domain competencies, as well as the general learning ability of the players. It is difficult to gauge the presence of optimal challenge until the actual responses of diverse players toward the tasks are iteratively observed. In the E-Rebuild project, we have iteratively retuned the usability of the interaction controls and training levels and emphasized sequential embedding of novel challenges and mechanics in game levels to present a positive slope of the learning curve.

On the other hand, an assumption of game-based knowledge development is to reinforce a scientific attitude, such as the persistence toward frustration from bottleneck as well as independent problem-solving. Design efforts to increasing the players' game engagement level by chunking and reducing the complexity of a game task, or the arrangements of external help from peers or experts, can reduce the chance for players to practice the scientific attitudes. It remains hazy as to when frustration is positive for scientific attitude development and through what observable behavior tracking we can gauge such a state adaptively for different learners.

### *7.3.3 Learning and Assessment Integration*

An implication of our design inquiry of E-Rebuild is to design and use games as both a learning and an assessment tool to enable gradual learning progression along with evidence accumulation for assessment in the game setting. An integral design and development of the tasks that scaffold learning while discerning competency status is achieved via evidence-centered learning task design and data-driven performance tracking. Specifically, we need to construct a learning trajectory (across game tasks) that maps (a) the interrelationships among the sub-competencies (and their observables), (b) the complexity level of each and every learning tasks (e.g., based on the required domain competencies, the internal complexity, amount of information, and disclosure of information in a game-based contextual math problem), and (c) the correspondence between the former two facets.

The actual process of interweaving game-based task and assessment development in E-Rebuild includes five interactive design sectors: (a) designing templates of tasks based on the selected gaming actions that *necessitate*, as well as the scenarios that *frame,* the practice of the targeted competencies; (b) setting the gameplay rule and reward system that scaffolds mathematical practices; (c) developing and organizing tasks based on the competency, evidence, and task models; (d) drafting the game logs, including the specification of in-game performance observable variables, along with the assessment statistical model (e.g., a Bayesian inference network); and (e) testing, refining, and validating the feasibility and effectiveness of the tasks and assessment models. The ordering of these core design sectors refers to their operational sequence in our game design process.

More design investigations on the interaction and alignment between learning task and assessment mechanism design are warranted. In particular, it remains inconclusive as to whether the pacing and mode of learning progression is fully coherent with those for performance evidence accumulation. In other words, the learning trajectory may not be fully overlapped with an assessment trajectory. The rule that decides the selection of a sequential learning task after a failed trial can differ from that of selecting a task for better evidence collection and diagnosis.

## 7.4 Other Analytic Generalizations on Designing Game-Based Learning Platforms

A few other analytic generalizations (Yin, 2003) have emerged from our phenomenological inquiry of the E-Rebuild design and can jointly contribute to the future development of a design theory for game-based learning platforms. These emergent generalizations, as outlined below, define functional and unique properties of the mechanic, interface, and player support in an educational game:

- *Game actions* should act as the foundation entity for the integration of learning and play in game mechanics development. Defining the basic actions that embody the essential content-rich practice helps to explicate the nature of learning and gameplay. Derived from the action specification will be the description of its structure (e.g., its objective and execution rule), potential obstacle (e.g., challenge or constraint), and meaningful context (e.g., the backdrop setting or an environmental story). Consequently, core gameplay for learning is defined.
- A *bicentric mode* (e.g., fly-through mode) of play improves game engagement as well as the game's functional and cognitive interactivity. It features a naturalistic coordination between egocentric and exocentric perspective in the interactions (Dede, 2009). Compared with either elevation or orthographic view, a bicentric perspective facilitates multimodal representations, both grounded and abstract, for the user's construction of visual-spatial schemata in encoding game objects and worlds, thus assisting them in investigating the game-based, contextualized math problem.
- An *intermediary interface* is the extension of an intuitive control to promote action-related, content-rich theoretical thinking. It is characterized by an active prompting that necessitates an overt presentation of *purposive*, *strategic*, and *domain-specific* cognitive engagements during the user input. An intermediary interface should enhance cognitive interactivity while maintaining adequate usability (or functional interactivity).
- A *mixture of granularity levels* of the simulated interactions (e.g., building with coarse-grained versus fine-grained units) enables the emphasis of different domain-specific competencies. The finer granularity level an interaction has, the higher procedural complexity it presents, and the more engagement in strategic planning (e.g., in selecting the most efficient procedure) it will motivate.
- *Dynamic learning support* should be interactive, and intrinsically integrated into the game mechanics, the interaction interface, and/or the game scenario. It should clearly convey its significance on the immediate game action and the later play experience to the game players. The agency of learning supports can

be compound: Learner initiated, system controlled, and human agent presented. There is an interaction effect between the presentation formats (symbolic or iconic) of the in-game supports and the task complexity in promoting game-based conceptual understanding and procedural skills. We also found that disadvantaged learners tend to be passive in requesting help and hence should be provided with more system- and agent-initiated learning supports.

## 7.5 Future Design and Research of the Game-Based Learning Platform

### *7.5.1 Co-construction of a Library of Design Cases or Chronicles*

Game design is a vastly ill-structured problem. A generic, versatile game design framework can foster a generic understanding of the design process and constructs, but will come short of guiding a specific design project. Moreover, the learning purpose and the requirement of cognitive interactivity of an educational game make the design of knowledge-conveying gameplay significantly different from the design of entertaining gameplay. Differing stances and cultures in relation to domain-specific knowledge and practices will mediate the design goal and problem formulation and make the design problem space even more indeterminate.

An ecological solution to the aforementioned challenges, as this book illustrates, is for members of the game design community to purposefully record and analyze their design exploration and problem-solving experiences and then share and archive their retrospective analysis results along with the design chronicle via a design case library or database. It appears that game designers have already developed the culture of blogging about their game design processes. Building on such a culture, gathering and archiving differing design cases while constructing a common symbol or representation system of the design concepts and knowledge should be applicable and vastly helpful to the community of game-based learning designers.



### *7.5.2 Design Solution Generalization and Participatory Level Design*

As the prior game design research and this project demonstrate, the design of game-based learning platforms requires a longitudinal, iterative design, testing, and refinement process. At the same time, using a game-based learning platform in school typically requires that the platform should be scalable to enable a continuous development or localized customization of game tasks based on a dynamic competency model and the varying needs of diverse school or class settings. The challenges of using games for learning, therefore, are to find generative methods that allow game tasks to be created cost-effectively and enable users' (e.g., teachers') customization of game levels. Even through automatic game design or level development has been a prominent theme in game design research (e.g., Butler, Andersen, Smith, Gulwani, & Popović, 2015; Nelson & Mateas, 2007; Togelius & Schmidhuber, 2008), the exploration of automatic design solution generalization in educational game setting is particularly limited.

Analyzing the basic design features and patterns of successful design solutions (e.g., engaging and effective game tasks or levels) is the starting point for automatic educational game design or level development (Butler et al., 2015). The evidence-centered task development in the E-Rebuild project has integrated the idea of using a set of semi-structured task templates that are defined by a set of key task parameters. For the future, we will experiment with a *parameter-based level development approach* (Sorenson & Pasquier, 2010) through which teachers can customize the values of a set of game parameters and task variables that define the basic features of a game level (or task) so that game levels can then be generated dynamically.

### *7.5.3 Adaptive Learning Support Based on Real-Time Assessment*

Another potential extension of the current integrative design of learning and data-driven assessment is to use real-time diagnostic assessment to drive adaptive and unobtrusive in-game learning support. Engaged gameplay may not guarantee successful math learning for all players, especially for those who lack the habits and skills associated with critical and reflective thinking. Adaptive scaffolds for action-based, metacognitive learning should be designed via unobtrusive in-game learning support, such as game task selection, regulation and reflection of content-specific gameplay, intrinsic learning prompts, and the balance between regulation and autonomy (Chang, Wu, Weng, & Sung, 2012; Wouters & Van Oostendorp, 2013).

By leveraging the stealth assessment mechanism, one can develop and experiment with adaptive in-game learning support that consists of (1) a customizable trajectory of gameplay, such as an optimum selection of game tasks, enabled by the user control of the parameter-based level development and (2) an adaptive and optimum level, form, and timing of scaffolding that integrate user initiation (autonomy) and computer regulation. Learners' interaction with in-game learning support features can also be captured as further input evidence to substantiate the developed Bayesian networks.

AU3

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| AU2 | Please check sentence starting "Environmental regulations of..." for completeness. | |
| AU3 | Reference "Goel & Pirolli (1989)" was not cited anywhere in the text. Please provide in-text citation or delete the reference from the reference list. | |

# Index


**A**
Amory's game object model, 6
Anti-earthquake building, 60
Architectural artifact, 67
Architectural Terms and Principles document, 53, 55
Architecture-themed scenarios, 106

**B**
Bayesian network model, 118
Bicentric mode, 150
Brick-by-brick approach, 95
Building modes of play, 83
Building-themed gameplay, 80

**C**
Chromebooks, 97
Chunked *vs*. holistic task, 109
Coding game mechanics, 18
Coding game objects, 64
Cognitive engagement, 87
Cognitive interactivity, 5
Collaborative design, 17
  interdisciplinary, 17
  students, authentic and constructive learning, 17
Comma-separated values, 117
Commercial off-the-shelf (COTS) games, 2
Common Core State Standards for Mathematics (CCSS-M), 45
Common symbol system, 146
Competency models, 54, 112
Consequential design, 90
Construct-centered assessment, 103
Content problematizing, 124, 126
Core game action, 18, 62
Cross-cultural communication, 9

**D**
Desert and historical rural pueblo, 97
Design aids, 72–74
Design-based investigation, 105
Design-based research, 7
  approach, 104
  findings, 102
Design chronicle, 20, 145
Design execution, 62, 65
Design goal and space, 72
Designing gameplay, 18
Designing games, 9
Design parameter and game reward mechanism, 61
Design principles/strategies, 148
Desirable situation, 2
3D game world, 94, 131
Digital games, 122
Downscaled map and game space, 98
3D rotation task, 95
3D sandbox games, 94–95
3D virtual world, 94, 127
Dynamic learning support, 150

**E**
Educational game, 19
Educational game design, 4, 9
  approaches and features, 6






F. Ke et al., *Interdisciplinary Design of Game-based Learning Platforms*, Advances in Game-Based Learning, https://doi.org/10.1007/978-3-030-04339-1

Educational researcher perspective, 6
E-Rebuild creation, 20
E-Rebuild design, 42, 98
  architectural design and building, 43
  data mining approach, 44
  designing an educational game, 43
  elevation view, 48
  interdisciplinary design, 48
  interdisciplinary process, 42
  interdisciplinary projects, 46
  learner, 42
  principal designer, 42
  role and responsibility, 43, 47
  teamwork, 49
E-Rebuild game, 46
E-Rebuild game actions, 88
E-Rebuild game levels, 80
E-Rebuild gameplay, 47, 61
E-Rebuild gaming sessions, 128
E-Rebuild learning program, 104
E-Rebuild participants, 95
E-Rebuild project, 42, 80, 149
E-Rebuild prototype, 116
E-Rebuild team, 45, 67
Evidence-centered assessment design approach, 112
Evidence-centered design approach, 19
Evidence-centered task development, 152
Exemplary design cases, 73
Exemplary design document, 113
Experiential gaming model, 6
External scaffolding, 125, 139

**F**
Failure-driven learning, 92
First E-Rebuild level, 70
Florida Mathematics Standards (FMS), 45
Florida State University, 42, 45
Fluky psychology, 90
Forgiveness, 93
Formal math notations, 106
Functional interactivity, 5

**G**
Game actions, 87, 150
Game-based knowledge development, 149
Game-based learning, 8, 9, 18, 19, 90, 101, 122–126
  assessment, 64
  contexts, 121
  engagement, 63
  environment, 19
  experience, 144
  platform, 18
  support, 19
  system, 19
  tasks, 19
Game-based math learning assessment, 117
Game-based problem-solving performance, 35
Game community mechanisms, 123
Game conversations, 92
Game data-driven assessment, 140
Game design, 9, 16, 144, 151
Game goal, 81
Game level prototype, 107
Game levels
  embedded mathematical concepts, 69
  experimental findings, 70
  exploration, 67
  game-based math problem, 68
  learning game, 71
  problem statement, 67
  structuring and navigation, 68
Game level sequencing, 71
Game log structure draft, 66
Gameplay, 4, 20, 61
  brick-by-brick approach, 95
  building-relevant gameplay, 87
  building-relevant mathematical experience, 82, 85
  building-themed gameplay, 81, 82
  cognitive and content engagement, 88
  components, 78, 80
  content engagement, 87
  core game mechanics, 79
  3D building materials, 88
  design conjecture, 87
  design effort, 80
  design hypotheses, 86
  design research findings, 80
  design team members, 80
  disciplinary knowledge/epistemology, 82
  3D modeling tools, 79
  E-Rebuild, 79
  game mechanics, 78
  game studies, 78
  granularity level, 86
  iterative testing, 87
  learning constructive, 87
  literature review, 79
  mechanics, 78
  narrative aspirations, 79
  open-ended game, 79
  play preferences, 81

  player perception, 81
  rules, 78
  skill/content, 77
  team members, 82
  user-testing findings, 88
Gameplay and learning, 2
Gameplay exploration, 59
Game programmers, 58
Game programming, 65
Games and simulations, 103
Games for learning, 8
  epistemic practice, 3
  experience design, 5
  game design, 5
  game-based learning, 2–3
  gameplay, 1
  knowledge, 2
  knowledge acquisition, 3
  learning and play, 1
  MDA, 5
  play and learning, 2
  player's perspective, 4
  scientific attitude, 3
  teaching and learning context, 2
Game space, 131
Game task design, 102
Game World design
  architectural scenarios, 96
  environmental settings, 97
  environmental storytelling, 96
  formal mathematical notations, 99
  pictorial presentations, 99
Gaming, 77
Gaming behavior analysis, 95, 110, 130
Gaming behaviors, 110
General reasoning abilities, 89
Generic design models, 143
Google SketchUp, 96
Guessing and trial-and-error behaviors, 110

**H**
Highlighter tool, 64
Human-computer interaction, 63

**I**
In-game scratch pad, 23, 135
Initial game level, 69
Instructional support, 124
Interactivity, 5, 9, 18, 19, 34, 35, 145
Interdisciplinary collaborative design, 17
Interdisciplinary design activities
  architectural concepts and skills, 53
  architectural design case, 57
  core game mechanic, 59
  description, 52
  design execution, 62
  design inquiry, 60
  design inspiration, 53
  design pattern, 51, 54
  design problem roots, 53
  design solution, 60
  discipline-specific design, 57
  E-Rebuild development, 51
  gaming-driven design exploration, 53
  graphical competency models, 53
  math learning, 52
  mathematical context problems, 53
  model sketching, 62
  modeling and cataloging, 54
  team members, 52
  technique, 52
Interdisciplinary design team, 72
Interdisciplinary educational game design, 16
Interdisciplinary research and interdisciplinary design, 49
Intermediary interface, 150
Intermediary user interface, 94–96
Internal scaffolding, 121
Interweaving game-based task, 105
Intrinsic knowledge integration, 147
Iterative player testing, 20

**K**
Kiili's model, 6

**L**
Learnability and playability, 87
Learner autonomy, 148
Learning and assessment integration, 149–150
Learning system designers, 58

**M**
Mathematical equation, 134
Mathematical knowledge and skills, 90
Mathematical planning and reasoning, 92
Mathematical problem-solving, 111
Mathematical reasoning, 59
Mathematical reasoning and calculation, 91
Meaningful play, 5, 147–149
Mechanics, dynamics, and aesthetics (MDA), 4

Metacognitive learning, 152
Mindfulness, 110
Multimodal cues and feedback, 135
Multimodal in-game scaffolds, 137
Multimodal math story problem, 106
Multisensory rendering environment, 1

**N**
National Science Foundation (NSF), 44
Nongame educational settings, 6

**O**
Open-ended game world, 126

**P**
Parameter-based level development approach, 152
Phenomenological examination, 10
Phenomenological perspective, 15
Physics Playground, 44
Pictorial presentations, 106
Plan and elevation views, 84
Post-level game performance badges, 138
Price bulletin board, 137
Problematizing mathematics, 3
Problem-solving efficiency, 92
Problem-solving performance, 110
Problem-solving skills, 116
Process-oriented data, 103

**Q**
Q-matrix, 113, 115
Qualitative data, 16

**R**
Reflective inquiry, 3
Retrospective analysis, 112
Row house, 108
Rural farm, 97

**S**
Scaffold players, 133
Scaffolding, 125, 133, 140
School set design, 131
School stadium building level, 132
School stadium level, 132
Self-determination motivation theory, 7
Stealth assessment, 46
Stealth assessment mechanism, 152

**T**
Task archetypes, 106
Task-based skill practice, 103
Task construction, 103
Task model, 113
Trading and building actions, 27
Transaction fee, 112
Treasure hunting, 89

**U**
Urban school, 98

**V**
Variables chunking and escalation, 130
Verbal/syntactic task description, 99
Video- and screen-recorded gaming behaviors, 110