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Jensen, Erik Ottar; Hanghøj, Thorkild; Misfeldt, Morten

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Game Design and Development as Mathematical Activities: Proposing a Framework

Erik Ottar Jensen, Thorkild Hanghøj and Morten Misfeldt
Aalborg University, Copenhagen, Denmark
eoje14@student.aau.dk
thorkild@hum.aau.dk
misfeldt@learning.aau.dk

Abstract: In this paper a framework for describing some of the mathematical activities inherent in computer game design is proposed in order to develop a framework for use in a recently conducted pilot study. The paper presents an introduction of previous work on the subject of game design and mathematics education which have mostly been tied to students making learning games involving specific mathematical content. Game design activities are reported to have a motivational pull for students. A challenge seems to be that the students are mostly motivated by the game design or the programming activities, not by understanding the mathematical content they are designing their games about. This and the authors' own research have led to a need for articulation of the inherent mathematical activities that exists in game design. This is done through a theoretical framework with three aspects. The first is called *domain-specific challenges* and introduces a way of looking at game-based educational activities as a negotiation of meaning between knowledge practices and describes the role of contexts in mathematics education. This aspect is used to understand how students perceive valid mathematical activity in the relations between the game design process, mathematics as a subject, the pedagogical practices, as well as the students' everyday experience with games. The second aspect presents *algorithmic thinking* and *systems thinking* as a basis for thinking in causalities, stochastic processes and consequences, which relates to mathematical activities in two ways; developing computer games though programming languages can relate to algorithmic thinking and systems thinking is related to the game design process. The third aspect is the *instrumental approach* to computational artifacts mediation as a means of understanding the mediation between user and goal through the computational artifacts being used. The framework serves as a lens for making sense of computer game design as a context for learning mathematics.

Keywords: Game design, mathematics education, systems thinking, student designers, math game, Algorithmic thinking.

1. INTRODUCTION

Game design activities are increasingly being used as an activity in relation to mathematics (e.g. Ke 2014; Valente & Marchetti 2012), but there is still limited research on mathematical learning through computer game development (Ke 2014). This paper outlines different aspects of computer game making activities in mathematics and aims at generating specific knowledge about what mathematical elements and processes a focus on computer game making activities allows.

For the purpose of this paper we want to make a clear distinction between game *design* and game *development*. We define *design* of a game, as the making of the formal structure of a game in form of the abstract guidelines that in turn define how the game system functions (Salen & Zimmerman 2004 p.117) - making the rules of the game. We define *development* of a game as the technical process of programming the game in a programming language on a computer. When we use the term computer game making we assume that this process both involve design but also development of a game. It is clear that these two processes might be highly intertwined in a game making process and that they arguably are difficult to separate entirely in actual activities. The reason for making the distinction between *design* and *development* is that viewing the two as separate entities, offers an opportunity to see distinct and different mathematical aspects of both development and design as defined above.

1.1 Game design and mathematics

Game design and development has been suggested for educational purposes by a number of scholars. The research literature on game design is often related to a general discussion of on viewing students as producers and enhancing student creativity (Loveless 2002). But other parts of the literature also relate more directly to STEM learning in the sense that game development has been promoted to teach coding and computer programming (Misfeldt & Ejsing-Duun 2015; Resnick 2012) and the redesign of games has been seen as a means to obtain system thinking competences, which allow students to become aware of relations between input and output and various modeling dynamics (Salen 2007). A number of scholars have investigated how learning of mathematical concepts can be achieved through student design, development and programming of learning games involving a particular mathematical concept - What do students learn about fractions when they make a learning game about fractions? (e.g. Kafai et al 1998; Valente & Marchetti 2012; Ke 2014). The underlying assumption for this approach is that the reformulation, articulation and application of the mathematical concepts through a design process, serves as a medium for learning mathematics. One challenge for this approach is that students' games can easily adopt a classical edutainment style where game and mathematical content are presented in non-situated practices. The student design thinking involved tends to be more focused around the game world, game story, and the programming of the game, rather than interacting, exploring and implementing the mathematical concept (Ke 2014). Another approach for connecting mathematics and game design is to investigate the individual mathematical concepts in a given game on a given programming environment. Here the assumption is that the production of games naturally exposes the students to the mathematical concepts involved in the game production. E.g. by understanding the particular mathematics of a maze, shooter or platform game when programming these in a particular environment. One challenge in this approach is the formalization of problem-solving within the activities because the students are more interested in designing and programming the game than learning mathematics (Shaw 2012).

1.2 Research question

When conducting the pilot study we faced similar challenges of what have already been described when attempting to connect mathematics and game design. Connecting student activities to specific mathematical concepts is a challenging proposition and the introduction of both game design and programming activities can hinder student interaction with the mathematical concepts proposed by the researchers or teachers. At the same time researchers document how designing and programming games is a highly motivating experience for the students (Vos et al 2011). In addition to this, the preliminary conclusions from a recent pilot study points towards the importance of the relationship between student activities and mathematical content for the production of meaningful mathematical knowledge (Jensen et al 2016). This led us to speculate on how game making in itself can be considered a mathematical activity. Not as a part of making a learning game about a particular mathematical concept or through the mathematics used in a particular game development environment. In that sense this paper does not attempt to create activities that teach specific curricular concepts or topics, rather we aim at understanding and articulating the inherent mathematical activities that exists in game design and development. This leads to the research question being investigated in this paper:

"*What are the mathematical aspects of computer game design and development activities?*"

We aim at focusing directly on mathematical aspects of computer game making activities by developing a simple framework for describing some of the mathematical aspects of game design and game development activities. We will do that based on a short reading of the literature around game design and education. The intention for the framework is that it can provide a better understanding of student interaction with the mathematical content in game making activities and serve as a lens for making sense of game design and development activities as they unfold in a real world instructional setting and as an inspiration for research and instructional design (Gravemeijer & Cobb 2006).

2. Discussion - towards a framework for mathematical game design and development

The framework we propose to think about mathematics in relations to computer game design and development incorporate aspects presented in the following sections.

2.1 Domain-specific challenges

Game design and development can be regarded as a context for learning mathematics, which involves the specific challenges and potentials that game-based learning offers. Hanghøj (2013) argues that game-based education can be understood as an interaction between four domains: the academic domain, the pedagogical domain, the everyday domain and a specialized domain, each containing specific ways of perceiving knowledge as valid. The academic domain relates to specialized knowledge practices within the scientific discipline, such as physics or mathematics. The pedagogical domain relates to the organizational knowledge practices related to educational institutions. The everyday domain relates to non-specialized activities practiced outside the classroom. Finally the specialized domain relates to the fictional domain being made through the use of games in education and is characterized by knowledge practices related to the game domain. Game-based learning often creates tensions between the four domains because each contains specific criteria for what counts as valid knowledge. Game-based learning should be understood through the interaction between the four domains and the on-going negotiation of meaning of knowledge practices across the domains (Hanghøj 2013).

Understanding game design and development activities in relation to the four domains becomes relevant for mathematical learning when game design is conceived as a context for learning mathematics. Using different contexts in mathematics teaching have been discussed by a number of scholars (e.g. Boaler 1993; Van Galen 2013). According to Boaler (2015) contexts in mathematics teaching should only be used when they "*are realistic and when the contexts offer something to the students, such as increasing their interest or modeling a mathematical concept. A realistic use of context is one where students are given real situations that need mathematical analysis, for which they need to consider (rather than ignore) the variables*" (Boaler 2015, p. 53). The ability to use domain-specific knowledge regarding the context and informal solution procedures is considered an integral part of mathematics learning (Gravemeijer & Cobb 2006). A context should support the students in using informal knowledge and it is more important that the mathematical problem is embedded in the context than whether or not the students regard the context as interesting (Van Galen 2013). Understanding specific game design activities through the four domains is proposed as a way of handling the concept of real context in mathematics, enhance learning outcome and provide insight into how specific design and development activities should be constructed.

To provide an example of how the domains interact in an educational game based setting we present a case from the project *Creative Digital Mathematics.* Here, teachers are creating lessons for students who are supposed to design board games using Geogebra (www.geogebra.org/). Through the teacher's intentions and hypotheses of students working to create a card game with different ice cream shapes, we can see how this activity relates to the different domains. The teacher states that the idea for the game is similar to trading cards such as car cards or football cards. This statement refers to the everyday domain in a sense that there are criteria's for valid knowledge regarding the specific type of game and knowledge about ice cream. E.g. how an ice cream is designed will affect if students perceive the representation as a valid ice cream or a drawing of something else. Another intention for the lessons is to have a whole-class discussion regarding the different features the ice cream can have; weight, height, price, and smileys and thus the categories on the card. The activity of the whole-class discussion refers to the pedagogical domain in a sense that this form of interaction between students and teacher that is used in the school system. The teachers' intention towards the mathematical academic domain is that the students will use different geometric shapes to develop their ice creams. Finally, an assumption from the teachers is that the students will try to make a great game and explore how they can use Geogebra. This can be seen to relate to the specialized domain in the sense that they are using Geogebra as a game making tool. It can also relate to the everyday domain where the students have criteria's for what constitutes a great game (Misfeldt & Zacho 2016).

Giving student opportunities to incorporate domain specific knowledge from several domains are from this viewpoint considered an integral part of the learning experience, and underline the fact that the students should be able to use domain specific-knowledge not only from the academic mathematical domain but from everyday and scenario-based domains. As such, a focus on mathematics in a game design context must also take into account that students may have specific domain knowledge about games on different levels from different domains and that a focus on learning mathematics will be enhanced if the students can use this knowledge actively.

The point here is that students are more interested in making a good game than learning about specific academic knowledge in game making activities (Ke 2014) and they validate their experiences in terms of how it can help them make great games. This gives rise to the idea that a focus on learning mathematics in a game based setting should try to Incorporate and look for converging points between the different domains. The question becomes if there are mathematical ways of thinking that can help the students achieve their goal? What mathematical ways of thinking can help a student design and develop better games? This question will be investigated in the next section.

2.2 Thinking in causalities, stochastic processes and consequences

The second aspect of the framework focus on students' ways of thinking and reasoning associated with game design and development and assumes that algorithmic and systems thinking can form the basis for thinking in causalities, stochastic processes and consequences. When making computer games we have found that there are two areas closely related to mathematics as seen from the academic domain; one area regarding development through programming activities and one area regarding design activities. This section will describe how both areas from a mathematical standpoint can be seen as specific ways of thinking in causalities.

Development and programming: There are three predominant ways of thinking about teaching mathematics with programming:

- Students as producers in a constructionist learning perspective.
- Abstraction and concept formation through a process-oriented approach to abstract mathematics.
- Algorithmic thinking (Misfeldt & Ejsing-Duun 2015).

The constructionist approach suggest that students learn in a particular effective way when they are engaged in the production of artifacts they are emotionally involved in e.g. computer games. The production of the artifacts, enable the students to come into contact with powerful ideas (Papert 1980). Abstraction and concept formation or APOS theory is described as a general learning theory of mathematical concept formation which argues that a process-oriented approach to abstract mathematics can be based in concrete numerical computations (Misfeldt & Ejsing-Duun 2015). Both of these approaches can be seen as general pedagogical approaches whereas the ability to think in algorithms and procedures is promoted as an important learning goal in mathematics. An algorithm can be understood as a recipe whereas algorithmic thinking involves developing and executing algorithms as well as making machines able to perform algorithms. Algorithmic thinking describes students' ability to work with algorithms understood as systematic descriptions of problem-solving and construction strategies, cause-effect relationships, and events. Algorithmic thinking is strongly related to mathematical thinking and can be seen as creating the intersections between computer science and mathematics, but emphasizes specific and slightly different aspects than other types of mathematical thinking (Misfeldt & Ejsing-Duun 2015).

In a game development context, working with algorithmic thinking can be understood as students description of, or work with the causality and consequences present in the programming of the game and a prominent mathematical aspect related to programming activities involved in game making. As such, algorithmic thinking can be seen as a form of mathematical content that is embedded in the programming of a computer game.

Game design: A potential mathematical area when working with game design is related to systems thinking and the fact that playing a game can be seen as an enacted scenario, where causalities and stochastics constitute outcomes. Eric Zimmerman (2009) describes the underlying structure of games as being systematic and argues that every game has a mathematical essence in the shape of a formal system – the rules of the game. In order to design games, it is necessary to understand them as systems. Similarly, the process of designing games is an activity, which can promote systems literacy (Zimmerman 2009). Designing a game involves reflecting upon possible alterations and their relation to different consequences and requires an understanding of the systemic aspects of the game (Collen & Minati, 1999).

Weintrop et al. (2016) highlight systems thinking as being important for handling and understanding the problems the scientific and mathematical disciplines faces today. As mathematics moves more and more toward being a computational endeavor, systems thinking is described as one emergent component for the next generation of mathematics. They present five computational thinking practices associated with science and mathematics that focus on systems thinking.

- Investigating a complex system as a whole
- Understanding the relationships within a system
- Thinking in levels
- Communicating information about a system
- Defining systems and managing complexity (Weintrop et al. 2016)

To better understand the relation between systems thinking and game design, Salen et al. (2014) present several game design activities, where students work with game design through systems thinking. E.g. by designing the world's hardest or the world's easiest game to understand balance in games and eventually try to design a balanced game. To create the easiest and the hardest game students work with the relationship between enemy sprite parameters and how they affect the level of challenge in the game through modifications of speed, health, and damage parameters. In the activity students are expected to give examples of relations between different parameters and how they affect the challenge level for the player and how the game can be modified to unbalance or balance it. Here looking at a single component of the game such as enemy sprite damage, one would assume that if we increase the damage output of the enemy, it will be more likely to kill the player avatar and thus the game will be more challenging. But if we look at how the different components interconnect we might get a different picture. If the enemy sprite moves at a very slow speed, or the player avatar has superior maneuverability, the damage output of the enemy sprite becomes insignificant as there is very little likelihood that is will ever reach the player avatar. Through this activity balance is perceived as an emerging property that arises from the interconnections of the game components instead of being connected to a single component. In this way the students are working with the overall structure of a system and the fact that the dynamics of the system occurs among system components (Salen et al. 2014).

Systems thinking might hence offer an opportunity for students and educators to work with mathematical concepts through the design of the rules in the game and present an opportunity to work with a system as a whole.

We do not intend to make the argument that these are the only two mathematical ways of thinking related to computer game making activities. A specific game design and development process with a specific programming language might contain a wide range of mathematical concepts and programming activities in general can be understood as being related to other mathematical ways of thinking. But it seems that systems thinking and algorithmic thinking have the potential of empowering students to become better game makers and therefore creates an opportunity for the students to reach this goal through ways of mathematical thinking.

2.3 The handling of tools – epistemic and pragmatic mediation

The third aspect of our framework is influenced by the instrumental approach, which describes computational artifacts as mediating between user and goal (Rabardel & Bourmaud, 2003 in Misfeldt, 2013) and can be used as a general theory for understanding the use of ICT in mathematics teaching. A distinction is made between epistemic and pragmatic mediation, which can be understood as the difference between using technology to solve a task and learning with technology (Misfeldt & Ejsing-Duun, 2015). Games are artifacts that students care for and hence they will often have very specific ideas about how the game should work and look (Misfeldt, 2013). Such ideas have proven to be strong drivers for the appropriation of the mathematical tools involved. In the *Creative Digital Mathematics* project it is concluded that game design activities:

…might lead to easy adoption of GeoGebra, familiarity with appropriating GeoGebra for different tasks, a positive attitude to mathematics among the pupils, and a re-scoping of primary level mathematics in direction where the discipline play a part in constructing cultural artefacts. However, the fact that the pupils in the interventions reported here, mainly used GeoGebra for pragmatic mediations, suggests that open ended design tasks might not be well suited for the students main activity, and should be complemented with activities that addresses the use of GeoGebra for epistemic mediation (Misfeldt, 2013).

A similar conclusion has been drawn in relation to teaching programming with games as an artifact produced by students (Resnick, 2012).

An example of how the different forms of mediation can be seen is students working with LEGO Mindstorms. When building their robots, there is a distinction between students creating their own robotic inventions or building a particular robot following predesigned plans and finally being graded by their teacher according to the performance of the robot (Resnick 2006). The distinction between pragmatic and epistemic mediations can help understand whether the students are making games to learn something from the process or simply trying to reach a teachers goal. Here it could be argued that a programming environment like Scratch (scratch.mit.edu/) can be used to open up the black box of game design and make the development process accessible so there is an opportunity to understand how the game is working. Thus it can help student achieve a number of goals related to epistemic mediations.

This third aspect of our framework suggests that there can be different goals for a student working in a game making situation and different mediations through programming environments and mathematical concepts within these. Using this aspect as an analytical lens might offer insight into these goals and help the educator or researcher with possibilities for influencing the students towards epistemic mediation.

2.4 A framework for mathematical game design

In figure 1, we have shown game design and development as mathematical activities.

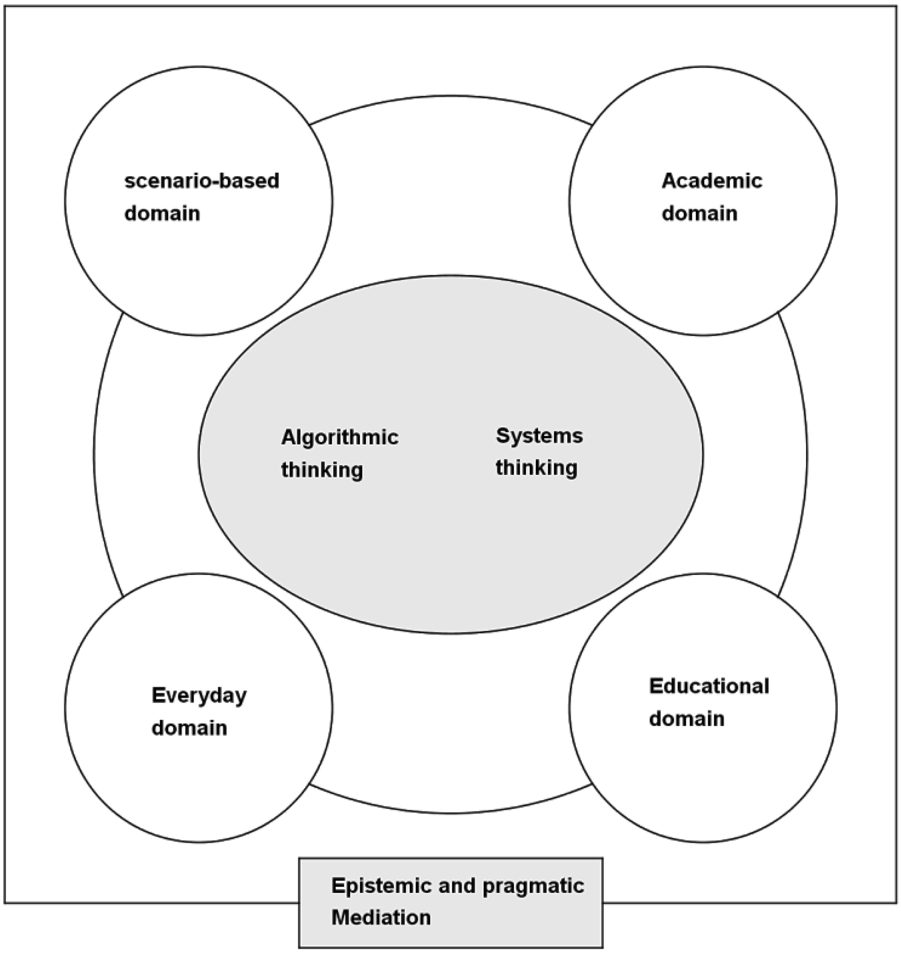

Figure 1

The figure shows the framework for thinking about mathematical aspects of computer game making as we propose. The first aspect involving domain-specific challenges gives us a focus for thinking the learning of mathematics as related to the areas where the different domains converge, not just associated with the academic domain. This aspect provides an overall frame for understanding the activity. The second aspect helps us understand some of the mathematical content that can be said to be inherently connected to the development and designing of computer games; Algorithmic thinking and systems thinking, which is embedded in the interconnectivity between the four domains. The final aspect, which concerns epistemic and pragmatic mediation, gives a general frame for understanding how different tools and activities mediate different goals in relations to mathematics teaching and learning.

To exemplify how this framework can help understand computer game design activities we present the student activities from our pilot study (Jensen et al 2016). Here the students were working in Unity with a runner game template. For each level of the game the students made a math question for the player. This allowed the students to design the difficulty level of the game. Several of the students were critical of the Unity template and one student would have preferred to use Scratch instead because it would have allowed him to "*make more [things] of my own*". Other students mentioned that the unity template did not allow them to change the narrative or key game dynamics and they unable to "*really make the game*" as the template only offered them the ability to change a few features within the game such as the graphics and mathematical questions. Two students stated that in fact they did not like the runner games at all (Jensen et al 2016). The framework invites us to ask questions regarding this game design experience through the three different aspects. What domains and knowledge practices are at work here and does the game design experience invite the students to use experiences from their everyday domain or from a specialized (game) domain? Are the students engaged in algebraic thinking or systems thinking or are they engaged in mathematical activities not inherent in game design? What kinds of mediations are present between the student, programming environment and activity and how can they be considered pragmatic or epistemic?

It seems to be a recurring theme for researchers that computer game design can hinder the students' interaction with the mathematical content being focused on by educators. This framework offers an opportunity to think about this relation. Not in the sense that specific mathematical content should be placed in a game design frame, rather that game design and development activities have embedded mathematical content. If educators are to use the motivational pull from making computer games to learn students mathematics, it seems that a better understanding of mathematics embedded in computer game design and development activities could help align mathematical goals and student goals. This framework provides an insight into these mathematical aspects and how a learning process of these could be understood. The framework can be used as a set of theoretical principles for educational design as well as a tool for analyzing mathematical learning in game design and development activities.

3. Conclusion

In this paper, we have described a framework for understanding how game making activities can be viewed as meaningful in relation to teaching and learning of mathematics. By looking at the literature around game design in education, we have articulated a framework consisting of three mathematical aspects of game design activities in a learning environment. These three dimensions, we propose, describe mathematical possibilities that it makes sense to consider when working with game making in mathematics and can be useful in informing a further development of understanding game design and development as mathematical activities?

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