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Outnumb3r3d: Intrinsically Motivating Mathematics for the PlayStation 4

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Abstract: This paper and accompanying poster describes the design of an *intrinsically integrated* educational game to improve children's competencies in mental mathematics. A number of researchers have suggested that educational games are more effective when they are closely integrated with their learning content. Specifically work by the lead author has showed that a closer integration between an educational game's core-mechanics and its learning content can be both more appealing (in terms of time spent on-task) and more educationally effective (in terms of learning outcomes) than a less integrated "edutainment" approach. However, cursory approaches to integrating learning content remain common in contemporary educational software, and the literature lacks an exemplar of what can be achieved using an integrated approach. The Outnumb3r3d game was conceived to provide a commercial and theoretical exemplar of intrinsic integration for the Nintendo Wii, but was never completed. This project is now porting the original Wii prototype onto the PlayStation 4 in order to revive Outnumb3r3d as a research project.

This paper details the design of Outnumb3r3d with reference to the key theoretical constructs that underlie its pedagogical design. In doing so it provides an example of a game design created to integrate mathematical learning content seamlessly into the game's core mechanics, ensuring that the mathematics is what makes the game intrinsically motivating to play rather than trying to hide or "sugar coat" its learning content. At the time of writing the game's implementation is still a "work in progress", but is expected to be the subject of future empirical evaluations into its effectiveness as a teaching tool.

Keywords: Game-Based Learning, Intrinsic Integration, Intrinsic Fantasy, Endogenous Fantasy, Mathematical Learning.

1. Introduction

Games with explicit educational goals have traditionally failed to inspire mainstream gaming audiences, yet the ever increasing prevalence of gaming in the home ensures that game-based learning remains a significant lure for educationalists. Based on the concept of *intrinsic integration* (Habgood, Ainsworth et al. 2005, Kafai 2001), this project aims to create a gaming exemplar which integrates mathematical content seamlessly into the core mechanics of an engaging console game. In doing so the aim is to create a gameplay experience in which the mathematics itself is what makes the game intrinsically motivating to play. The proposed game will be released as a digital-download product through Sony's PlayStation Network and make full use of game analytics to provide research data for subsequent analysis and publication.

2. Outnumb3r3d

Outnumb3r3d is a two-dimensional arcade game in which the player uses mathematics to defeat monstrous enemies advancing towards their tower (figure 1). The game aims to develop competency in tables-based mental maths problems, which underlie the ability to proceduralise many more complex problems in mathematics (Rittle-Johnson, Siegler et al. 2001). Each enemy has a numerical health value (above their heads) which must be reduced to zero in order to destroy them. The game is designed to take the player through a scaffolded progression from applying repeated subtraction and addition onto using multiplication and division as a faster way of dispatching monsters. This more efficient method eventually becomes critical to successfully defending the tower against waves of bigger and faster monsters. End of level "boss monsters" require the application of addition, subtraction, multiplication and/or division in order to successfully defeat them, as well as embodying more general mathematical concepts (e.g. even numbers, number sequences, prime numbers).

A working prototype of the Outnumb3r3d game was originally developed at Sumo-Digital for the Nintendo Wii platform. The prototype demonstrated the potential for this to be an engaging concept, but development ceased when the lead author left the games industry to pursue an academic career. This project is now being

revived as a research project using Sony Computer Entertainment's PhyreEngine to port the original code onto the PlayStation 4 utilising a PlayStation Move controller in place of a WiiMote.

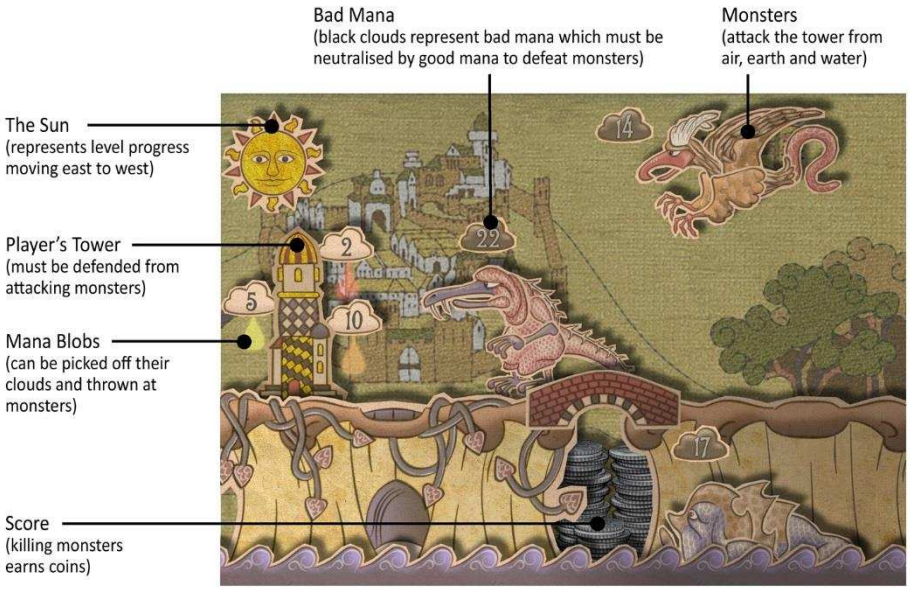

Figure 1: The Outnumb3r3d screen layout

2. Prototype design and development

The design of Outnumb3r3d is underpinned by previous theoretical and empirical research by the authors (Habgood, Ainsworth 2011) which proposed that learning material should be delivered through the flow experience (Csikszentmihalyi 1997) of a game and embodied within the structure of the gaming world and the player's interactions with it (i.e. the game mechanics). The game design was inspired by XGGen Studios "Defend Your Castle" which is a frantic arcade-style interpretation of the tower-defence genre. The core mechanic is more focused on the active physical defence of territory than strategic placement of defending units. It was originally felt that this kind of game could be a good fit for the proceduralisation of mathematical learning content as well as having low development costs due to the limited content requirements.

Development work on Outnumb3r3d began by building a GameMaker (Habgood, Overmars 2006) prototype to explore the playfulness of a game mechanic based around wielding elastic blobs of liquid. The blobs were modelled using a set of constrained springs and rendered using a threshold-based 2D metaballs approach (Chang, Lei et al. 2007). A simple animation system was implemented for the monsters which physically connected them with the environment and allowed them to wrestle and punch the player's tower. The physicality of the initial prototype provided an enjoyable playful experience and so development continued on the mathematical elements of the game.

The flow experience derived from games like "Defend Your Castle" comes from the frantic 'blow-by-blow' interaction with the castle's assailants, so the learning needed to be placed at the heart of this interaction in order to make the integration effective. Numeric representations in games are most commonly associated with health and scores, so it was decided to provide each enemy with its own (dark) cloud representing its health. Similarly the blobs were given their own (light) clouds showing the subtractive power of different blobs and a range of clouds was attached to the player's tower. This formed the basis of the first prototype of the game which supported repeated subtraction as the only means of defeating enemies (figure 2, left).

At this stage development was moved onto the Wii platform using Sumo's in-house game engine and was given a graphical restyle inspired by the Aberdeen Bestiary (Beavan, Arnott et al. 1997). The division mechanic was introduced as a 'magical' version of subtraction, so that pressing the trigger button while holding a blob caused it to be magically enhanced. Once enhanced it could defeat an enemy in a single blow provided the enemy's mana was divisible by the value of the blob. This was accompanied by different particle effects depending on the divisor and resulted in a more impressive demise for the unfortunate enemy monster.

Figure 2: Outnum3r3d Prototypes. GameMaker (left) and Nintendo Wii (right)

The remaining design elements introduced repeated addition and multiplication as means of creating monsters to defend the castle in a similar vein. This meant that addition, subtraction, multiplication and division were all embodied as part of the game's core mechanics. Players could now combine mathematical strategies in order to dispatch enemies in different ways, resulting in different levels of tactical gameplay dependent on the player's conceptual understanding of division (i.e. being able to identify appropriate multiples of the available divisors). The final feature which was added to the game was an octopus-like end of level boss whose tentacles were all prime numbers which (therefore) couldn't be defeated using division attacks.

3. Adaptive learning content

Outnumb3r3d was never intended as a game which would have a prescribed level design, but one which would adaptively introduce content to match the ability of the player. One of the remaining technical challenges for the game was to implement an adaptive system which could scaffold the introduction of harder mathematical content without obviously limiting level progression within the game. This adaptive approach would mean that players' progression through levels will be based on improvement rather than attainment, with players of all learning abilities being able to experience the full range of gameplay offered by the game.

It is proposed that such a system should be based on a theoretical model of the different kinds of mathematical knowledge that contribute to competence in mental maths problems based around multiplication and division (e.g. Mulligan, Mitchelmore 1997, Robinson, LeFevre 2012, Squire, Bryant 2003). Such tasks involve dealing with symbolic representations, the numerosities that they represent, the connection between them, and the conceptual and procedural steps required to get from the problem to the action. This theoretical model would be used to implement a software model of players' mathematical knowledge in the game, and a supervised machine learning algorithm would be used to associate different in-game actions with different parts of the model. For example, dividing the number 12 by two may simply be an act of recall, but dividing 4768 by two is more likely to be associated with a conceptual understanding of odd and even numbers. The internal state of the model associated with each player would then be used to drive the range and difficulty of the game's learning content in order to try to keep the player within their Zone of Proximal Development.

4. Game analytics

Modern digital delivery platforms and analytical systems offer a huge opportunity for game-based learning research (Serrano-Laguna, Torrente et al. 2014). The scale and detail of data that could potentially be collected from popular videogames is staggering (Sifa, Drachen et al. 2013). Even an educational game on the PlayStation 4 will inevitably attract an audience significantly larger in size than any classroom evaluation. This project will seek to make full use of this opportunity to collect research data associated with the product and build in design features which can be comparatively assessed in order to inform the design of future educational games.

5. Conclusion

Outnumb3r3d's novelty is in providing a single, intrinsically integrated mathematical gaming context, in which all of the game's learning takes place. The game will deliver learning material through the parts of the game that are the most fun to play, riding on the back of the flow experience produced by the game and not interrupting or diminishing its impact (in the way that traditional edutainment games often do). It will embody the learning within the structure of the gaming world and the player's interactions within it, providing an external representation of the learning content (Zhang, 1997) that is explored through the core mechanics of the game. This ensures that the player remains engaged with mathematics at all times, and cannot easily circumvent its learning benefits. On top of this it will provide an adaptive learning experience which models player cognition and uses this to appropriately challenge the player and keep them in their "flow channel". As such we believe the primary appeal of Outnumb3r3d will be in the challenge of playing the game itself rather than any explicit desire for self-improvement, which would be a significant achievement for an educational game.

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