A novel format for scientific educational software inspired by expressive puzzle design

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***Abstract*—In this paper the virtues of computer games as tools for education are reviewed, and productive possibilities involving "expressive level-design", a set of techniques from the games industry, are considered. Existing examples of expressive level design being used for education are described. Bret Victor's "Scientific communication as sequential art", a novel format for educational software, is described, and possibilities and attempts at integrating the game design techniques with it are proposed.**

Keywords—educational software, puzzle, games, Bret Victor, mathematics, health, biology, viruses, neuroscience, science

I. INTRODUCTION

Jacob Habgood, speaking about the general approach to designing computer games with learning content, coined the phrase "chocolate covered broccoli" to describe them[2]: the implication being that the "games" consisted of textbook content alternating with interludes of simplistic "fun" gameplay and story content (such as "math blaster", a shoot-em-up where enemies occasionally pause fighting to ask players maths questions). Educational games have been designed in this way for years, and as he found, they have very little educational value. If we are to believe any sort of educational computer game is at all worthwhile, their design must be rethought.

In principle, the most important aspect of the computer for the educational applications that will be described in this paper is its ability to automate things. The education of maths and science involves the description of certain systems; students are expected to assimilate these systems by listening to a verbal description of them, then visualizing that description, then reading more exercises in order to test the internal model they have built. But why describe a system when one could automate it, using a computer, and allow students to directly experiment with it, and get used to its workings that way? A simple example would be "the graph of y=f(x)+A is the same as the graph of y=f(x) but moved upwards by a distance of A" - since learning this fact requires us to visualize it internally, why not visualize it on a computer?

It happens to be the case that when something is visualized on a computer with the intention that someone will tinker with it and then later be tested on their understanding of it, we are halfway towards talking about a computer game. Because games are almost always about players accomplishing certain challenges. Therefore it is worthwhile looking to well-liked computer games for advice about educational software.

II. TEACHING TECHNIQUES IN GAMES

A video game can be a moderately complicated -or at least unintuitive- thing. In playing a game, you are faced with a set of objects that have specific behaviours and relationships to one another - to give examples: "if object X and object Y touch, object Y will disappear and object X will grow larger", or "if the A button is pressed then object X will rise vertically until it collides with something, or if the A button is let go, or if the apex of a certain pre-defined arc is reached". It becomes very important that the player comprehensively understand the behaviours and relationships, because the point of the game will be to achieve something with the objects.

Anyone making a game must confront the question of how the player will learn the relationships and behaviours of the game's objects - learning the "nouns and verbs", as some designers refer to them[13]. Ideally the player must learn them in a way that avoids being intimidating or boring. This is not easy; the obvious method would be for the player to read a block of text about every new object, and though many games do things this way, successful designers will try to avoid text - because reading, *when one feels one ought to be acting,* is not fun. Other things being equal, we should aim to have the player learn while acting.

For the three-plus decades of the games industry's existence, good designers have attempted to *teach* players things using subtle methods that make "learning" indistinguishable from "playing". There are many interesting examples of this, in games including classic titles like *Pitfall*[18], *Super Mario Bros*[13], *Castlevania*[14], *Megaman*[16], and *Tomb Raider*[16]. New techniques are brought in in more recent games like *Half Life*[16], *Halo*[16], and *Portal*[3]. The details of these techniques is beyond the scope of this paper, but for the purpose of demonstration, one particular technique will be highlighted.

Figure 1: Catacomb Abyss. From [19]

Figure 1 is a screenshot of an encounter in the first level of the game Catacomb Abyss(1992). Anna Anthropy has described[19] the cleverness of this engagement. The game is a first-person-shooter in which the player is intended to make their way through mazes, shooting zombies. Certain walls of the mazes can be destroyed - but at this early stage of the game, the player is not aware of their ability to destroy walls.

Figure 1 shows a particular part of a level that is set up to teach players about wall-destruction. It is a very enclosed space, and the zombie on the right appears from nowhere - the reaction that most players will have to this is to fire multiple bullets towards it haphazardly. Most of the walls here are destructible - therefore there is a high probability that the player will *accidentally* hit a wall with a stray shot, see that they can be destroyed. They will thus have learned a behaviour in a natural-feeling, yet very much designer-intended, way. This level design technique is called "teaching through accident"[15], and has been used in a number of games including *Quake*[15], a game made by the same designers as *Catacomb Abyss.*

The designers of *Catacomb Abyss* did not have to do things this way - they could have had a text box flash up saying "you can destroy this wall and others like it by shooting it". But having the player learn this way would be inconsistent, a source of irritation, and less exciting. The technique was chosen because it allowed the educational engagement to be *concise, impactful, active,* and *fair*.

Concise means that the player mustn't have to repeat themselves or spend too much time on one thing. *Impactful* means that the concept taught must come through clearly and memorably. *Active* means that the player's agency must not be taken away; they must be acting, or allowed to act, so that the educational engagement does not seem out-of-place (ideally every new behaviour they see is in part triggered by an action of theirs; this increases impact). *Fair* refers to the fact that the player should never feel punished for not guessing something they couldn't have been expected to know. For example, if they fight an enemy that can throw grenades that can kill them in one hit, then they should have seen the enemy throw those grenades at some point previously; it would be cruel for them to find out about the devastating grenades by dying. This is similar to how, at school, a student should never be required to answer a question containing a word that they have never seen before.

Other nonverbal "expressive level design" techniques that sustain activeness, fairness, conciseness, and impactfulness include: "antepieces", the use of minimalist principles, "broken bridges", short-term rewards, and cinematographic techniques that guide the player's eye in the certain directions[9]. Many game designers know it is worth investing time into making use of these techniques, but educational game and software designers don't - even though they should be taking them most seriously of all.

III. Existing examples of expressive level design techniques being used for science education

The games using these techniques that should be of most interest to educators are *Portal, Miegakure, Braid, Velocity Raptor, DragonBox: Elements, Incredipede*, and *Music of the Spheres.* These are all puzzle games with mechanics inspired by maths and science - they prove that scientific concepts can be taught using these level design techniques; it is simply a question of how to embed them in the mechanics and objects of a game.

Miegakure is an as-yet unreleased game about learning to understand higher-dimensional spaces by moving around in them solving puzzles. This allows mathematical ideas previously only seen in university-level study to be fully understood by schoolchildren; it seems likely that we will soon be talking about educational software pre- and post-Miegakure[4].

Andy Hall's *Velocity Raptor* teaches players about the speed of light, and it is worthwhile to compare it with the educational game *A Slower Speed of Light* released by the MIT gamelab, which attempts to do the same thing. Though they have the same subject matter and essentially the same mechanics, the two games are in two different genres: *Velocity Raptor* is a puzzle game, and we would describe *A Slower Speed of Light* as a "sandbox" game - there are no goals given by the designer, and no particular obstacles, only an engine to experiment with. This makes it debatably inferior as an educational medium, because there are no *specific* "phenomena" within the engine that the designers are *guaranteed* to have taught to the player. Whereas with puzzles, a designer can be confident that a player who has completed the game has encountered those phenomena that the puzzle-solutions involve. Puzzles in this sense are what designers use to do to players what teachers do to students using homework. Non-puzzle games can be educational, of course, but not so specifically - and they won't be able to use the design techniques described here so well.

IV. Bret Victor's "Scientific communication as sequential art"

Recently, a novel approach to using computers to communicate was proposed by Bret Victor. It sits very much apart from educational games, but is highly worthy of consideration by makers of games.

Victor notes that many momentary concepts that scientists and mathematicians wish to express in their papers can be turned into interactive programs. He advocates that it is possible to do this quite elegantly and expressively using web-like environments, by alternating between text and applet-like windows. Scientists who are able to program may integrate applets as effortlessly as they would integrate pictures.

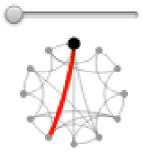

Figure 2: One of Victor's demos, from his translation of Strogatz et al's paper - the slider can be moved back and forth to rewire the network. Picture is same size as the demo appears in the paper – it is one of more than half a dozen.

Victor demonstrates the power of his idea by giving a "translation" of a seminal paper on the subject of network theory by Strogatz et al[6]. Like all maths papers this one contained a number of equations and wordy explanations of certain processes. Victor's translation involves taking these parts and, where possible, visualizing them; and in some cases making the visualizations into things that the reader can experiment with, using an intuitive slider. Where once an equation would be specified, there is now a something that automatically executes the equation based on inputs specified by the user.

The idea of using a computer to exhibit the behaviour of an equation is not new - this is one of the fundamental things that computers were designed for. But by effortlessly blending verbal exposition, images, and "applets", Victor is expressing something in a novel way. His approach has since been used by Amit Patel[10][11] to write about several things, and by the Khan academy in some of their online lessons.

In some sense Victor's approach to expression here, being mostly verbal, is very different to what happens in the games described in the previous section, where the whole point of using the design techniques is to eliminate the need for text. But there may be a format that we might call the "interactive documentary" which can get the best of both worlds: nonverbal systemic learning, and worthwhile verbal learning placed on top of it.

V. A MODEL FOR INTEGRATION OF EXPRESSIVE LEVEL DESIGN TECHNIQUES INTO A VICTOR-LIKE MEDIUM

Bret Victor's new medium, though influenced at the philosophical level by games like *Braid*[7], only uses mechanics to communicate, similarly to *A Slower Speed of Light*. Obviously, our first suggestion would be that communicative power might be expanded with the use of specific puzzles and design techniques.

As a proof of concept for this, Nicholas Swindale's paper "Visual Cortex: Looking into the Klein Bottle"[17] was selected as a subject for the kind of "translation" that Victor performed on Strogatz et al's paper. Swindale's paper is about the way that the brain stores information about straight lines that it sees, and how this information may be represented well on the surface of the curious object known as the Klein Bottle.

The translation of Swindale's paper included interactive demos that allow the user to, for example, make changes to a "sight" and see the visual cortex's response. It is still about half verbal exposition however, and the structure of the paper was retained.

The main difference from Victor's Strogatz translation is that this Swindale translation could be said to have puzzles. The text suggests certain challenges that the player *could* take on in their interaction with some of the demos. There is no reward for accomplishing the challenges, nor is there any withholding of progress. This was done to make things approachable, but sadly did mean that the "guarantee" of the player assimilating specific facts, described earlier, was compromised - ideally things would be streamlined such that more could be expected of players.

The project turned out to be too ambitious - playtesters were amused and intrigued by the demonstrations, but the expression was not clear enough for laypersons to understand the message of the paper, at least not on a single readthrough (although this is not necessarily a step down from the paper itself).

Another project was *The Stranger Loop*[12], which used the mechanics of the arcade game *Asteroids* to describe some basic mathematical topology. The novel thing is that it had a verbal narration, inspired by the games *Dear Esther* and *Bastion*. *The Stranger Loop* uses basic puzzles and does withhold progress, so there was the "guarantee".

The intention was that the audio narration would fill in the sensory gap that many games leave somewhat empty (many games have good music, but sound does not often *change* a player's thinking about the *system* of the game). The experience was expected to be documentary-like - if people can enjoy listening to David Attenborough's expostulation while watching something beautiful, why not listen to something interesting about a system while playing with it?

The Stranger Loop had some success - many players played and listened simultaneously, including Colin Northway and Ben Ruiz, who enjoyed it enough to call it "the future of education". However, some would stop playing in order to listen to the narration, and wait for it to come to the end of a segment, before continuing to interact, in spite of a system in place that was intended to synchronize challenge and narration timing. This is not exactly a failure; players were at least aware they the system was manifest, and in a state to be experimented with, so the narration was not intruding upon their mental model of their current "surroundings".

VI. CONCLUSION

The Stranger Loop bridges the gap between papers like Victor's translation and games like *Miegakure* and *Catacomb Abyss*. This was its intention: to offer a way to combine all the best ways of interactively teaching specific mathematical and scientific concepts into one artefact.

From the projects described here, both of the author's own and those of others, the lessons should be: 1) anything in science that *can* be given the visual-interactive treatment *should* be given it; 2) specific things about systems can be taught through puzzle design that is sufficiently perceptive in regard to human behaviour; 3) this method of education is often preferable to verbal exposition; 4) a documentary-style narration can be a pleasant addition to a game, and can be used to improve its educational value too, without intruding upon the player's experience. With all these in mind, the author's next project is a game based directly on a mathematical model from the study of viruses shells described in a 1962 paper[1] it will include both a narration and educational puzzles.

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