Serious Game for Quantum Research

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Abstract. In this article, we discuss the development and evaluation of a game designed to harness non-expert human intuition for scientific research in the field of Quantum Physics (Quantum Information). Since many physics problems are represented and analysed in a geometric space, we hypothesized that human predispositions such as geo-spatial intuition could be considered as a means to reduce the search space in some optimisation problems in quantum information which are currently solved through brute force approaches. We developed a 3D digital game in order to investigate players' ability to solve a known and quantifiable current research problem in quantum physics. In this article, we describe our motivations for conducting this work, the game design and its implementation, our experimental design and an analysis of the results obtained via player evaluation. Initial results are promising, indicating that players can indeed find known solutions to the example problem.

1 Introduction

While scientific games with a purpose are quickly proving themselves to be a viable and important tool in research, their emergence also amounts to a new computational paradigm – one of hybrid human and machine computation – in which human skills, biases and motivations must be harnessed with machine capabilities in order to find the most efficient way to solve problems. In general whilst machines are better at performing complex calculations quickly, human superiority in visual processing still makes them better at solving image recognition and geo-spatial problems. Finding a system that effectively utilises the capabilities of both could potentially lead to a significant acceleration of scientific research. The emergence of scientific Games With A Purpose (GWAP) represents an exciting opportunity for harnessing non-expert human intuition in the service of scientific research. Cooper et al [1] stated, "The integration of human visual problem-solving and strategy development capabilities with traditional computational algorithms through interactive multiplayer games is a powerful new approach to solving computationally-limited scientific problems."

From the perspective of serious games research, this leads to a set of research questions for an emerging field of scientific games: what sort of scientific problems are

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amenable to representation in game form? Which sorts of problems benefit from non-expert human intuition and to what extent does this approach outperform computational techniques? Quantum physics is an ideal field to explore these research questions. Very often the difficulty in solving quantum dynamics is due to the vast numbers of possible configurations allowed by quantum laws, such as the quantum superposition principle. In simple terms, the number of possible quantum states for a given system is exponentially larger than the “allowed” states of classical systems. As many physics problems are analysed in a geometric space, we believe that it is legitimate, in this context, to investigate human predispositions such as geo-spatial intuition as a way to focus on potentially fruitful areas of the search space. Very little is known about the potential for entertainment games to act as a resource towards solving complex research problems in quantum physics. In this project, we investigated the possibility to translate an open research problem of quantum physics into a game, encoding quantum rules into game mechanics. In the future we envisage a situation where massive numbers of online players (without any specific competence in physics) provide an essential contribution to research through immersive gaming activities. The GQR game represents a concrete step towards investigating the feasibility of this approach.

1.1 Related Work

A Game with a Purpose (GWAP) is a program that combines some meaningful task or purpose with elements commonly found in purely entertainment focused games. Marsh [2] defined a broader serious games continuum from ‘*video games with fun and challenging gameplay for purpose*’ to ‘*experiential and experimental environments with minimal to no gaming characteristics for purpose*’. Furthermore, fun gameplay has been identified as a powerful motivating factor [3,4] and thus represents a core aspect of game design in determining a GWAP’s potential in gathering data. McGonigal [5] stated that, globally, people now spend over three billion hours a week playing games online – it is this combined human effort that GWAPs hope to harness.

The most successful scientific GWAP to date is undoubtedly Foldit, a game where players fold simulated protein structures and attempt to find the lowest energy configuration [6]. So far over 57,000 Foldit players have assisted in directly improving at least two protein structures [7, 8]. Perhaps more interestingly, Foldit players have also been able to improve the folding algorithms used by commercial protein folding modelling software; this may have implications in computational complexity theory as protein folding is an NP-Hard complexity class problem [9, 10, 11]. That is to say, a solution to all protein folds is considered computationally intractable, so Foldit players being able to improve the algorithms used to solve specific instances of the protein folding problem is an interesting and exciting result.

A more recent example of a GWAP can be found at Aarhus University in Denmark where the CODER group is working on a ‘Quantum Computer Game’, a physics GWAP with the aim of solving an optimal path problem relating to the development of the quantum computer [12]. Though approaching a different set of problems in quantum physics, the Quantum Computer Game project is similar in many ways to the Games for Quantum Research project, as it aims to create a game that will allow non-expert players to generate valuable research data while having fun. The CODER group also aim to educate people about quantum physics research and the quantum computer through their game, although this is currently not one of our aims. Two other prominent scientific GWAPs include MIT Game Lab's 'A Slower Speed of Light' – a game that utilises a relativistic physics engine and hopes to teach players more about relativistic effects by letting them experience them in a 3D environment, and 'Galaxy Zoo', a citizen science project in which players identify astronomical phenomena in a large set of telescope images [13, 14]. The former fits into the middle of Marsh's continuum as an environment with fewer gaming characteristics.

It is clear that scientific games with a purpose are quickly proving themselves to be a viable and important tool in research. Another important aspect of scientific GWAPS, and Citizen Science in general, is that they help to bridge the gap between the scientific community and the general public. Scientific GWAPs can help the public engage with the research community in a way that they actually find enjoyable and is more participatory than many more traditional methods of outreach.

2 Game for Quantum Research

2.1 Motivation and Problem Selection

While the idea of using games for research and data gathering is not new, applying this approach to quantum physics introduces new challenges. Applying classical (i.e. non-quantum) physics in a game environment is relatively conceptually straightforward. In quantum physics, there are somewhat counter-intuitive aspects that do not relate to everyday experiences in the world. One such example is the superposition state, a linear combination of two distinct (mutually exclusive) states [15]. This has been famously illustrated by Schrodinger's example of a cat in a box. We know that there is a 50% chance that the cat has been killed, but without looking inside the box, we can't know which, so we say that the cat is both dead and alive at the same time. Whilst this is clearly not a sensible approach to cats, when we discuss superposition states in quantum physics, we realistically can talk about an atom being in two configurations at the same time. Because of this, it is impossible to simulate quantum mechanical systems on classical computers [16, 17]. When applying serious games to quantum physics, we considered three main criteria for selecting a problem. First, it was important to find a problem that could be visualised geometrically. This problem also needed to be one for which there were some solutions (in specific cases) so that we could gauge the success of the players in finding solutions. Finally, we chose a problem within the research interests of the group so that the project could contribute to the field in a useful way.

At its simplest, the game would be a data collection tool, allowing us to use players to generate datasets for later analysis. However, the aim of this project was also to harness the intuitive pattern recognition abilities of human beings, allowing for a more nuanced data collection than, for example, using random numbers to sample a space. Thus we consider both the question of whether players can find a solution, but also if players can find a solution more efficiently than with the standard approach.

2.2 Describing the Problem

The problem we chose is based on measuring information flow in open quantum systems. The quantum system of interest, such as a quantum bit (qubit), is interacting with an environment, such as transmitting information along a noisy channel. Because of this interaction, the qubit can lose some of the information, in the worst case making it unreadable at the output. One way around this is to minimise the interaction with the environment, however this is not always practically possible. An alternative is to choose the environment carefully to minimise the loss of information, or in some cases, even allow the qubit to regain lost information. We measure this capacity to protect and reinstate information, known as non-Markovianity, as the maximum regain of information over all possible initial conditions of the qubit [18, 19]. This type of problem is most easily visualised in quantum physics using the Bloch Sphere [Figure 1].

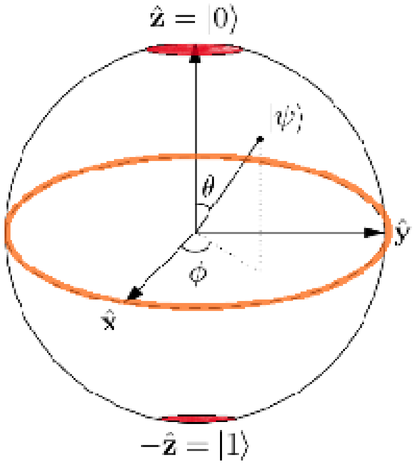

Fig. 1. The Bloch sphere, with the approximate solution areas given by the model highlighted. The z-axis solution areas highlighted in red are the main solution, while the equatorial band highlighted orange represents a region of non-maximal regrowth.

The Bloch sphere is a mapping of a quantum bit within the boundaries of a 3-dimensional sphere. In essence, the sphere represents all the possible positions of a qubit. The north and south poles represent the 0 and 1 states, respectively, which correspond to the 0 and 1 of a classical bit. Once you move away from the poles, the surface points correspond to the superposition states, where the qubit is both 0 and 1 at the same time in various proportions. In fact, every point on and within the sphere represents a valid qubit configuration. The centre of the sphere is known as the maximally mixed state, and is the state which holds no information because it's equally close to 0, 1 and any superposition of them.

As the qubit evolves in time, it moves within the sphere. If it moves closer to the central point (shrinking), it loses information, but if it moves away from that point (expanding), it is regaining information. If instead of looking at a single point, you look at all of the possible initial points, you can see the initial sphere (the set of all possible states) shrink and expand as information flows into and back from the environment. Because different states will lose and regain information at different rates, what is initially a sphere will deform and change shape over time. To measure the non-Markovianity, we need to find the point with the most regain of information, i.e. the largest regrowth away from the centre of the sphere. In some systems, this point is known, however in general it is not, and changes from system to system. To find it, we usually take a random sampling of states, and followed through time individually, taking the maximum value from that set of states. In order to get the best result, a large number of points must be taken, however this is both time consuming and gives little physical intuition to the problem. By allowing human players to visually follow the time evolution of the whole sphere at once, and identify the largest areas of re-growth, we aim to both shorten the process and give researchers a more intuitive picture of the process.

2.3 Game Design

The GQR game we developed focused on identifying qubit states for which information back-flow is maximal [20]. This specific problem was selected for two main reasons. It can be represented within a simple 3D geometry [Figure 1] and due to its simplicity, an answer can be determined, thus providing a benchmark for assessing GQR's potential in gathering relevant and useful data.

In the GQR game, the player is placed at the centre of the Bloch sphere (above) and tasked with shooting the inner surface at the point where they see the largest regrowth from a previous minimum; each shot they take is scored based on this. The environment is dynamically modelled and the sphere is in a constant state of deformation. In the prototype we consider the simple case in which there is only one time interval in which information back-flow occurs and hence only one time interval in which regrowth can be seen in any given direction. The sphere itself is represented by a large spherical grid (Figure 2).

Each play of the game lasts 60 seconds, running through the full system dynamics three times per play. The idea is that the player will familiarise themselves with the game during the first 20 seconds, examine the Bloch sphere dynamics within the second 20 seconds and take their best shots during the third 20 seconds. At the end of each play-through, the game records the highest score the player managed to achieve along with the vector co-ordinates of the shot and the time at which it was taken. In order to motivate the player a game must include elements of challenge, so obstacles or 'enemies' were added to the game that move around and attempt to block the players shots. As well as motivating players this also prevents them from simply firing

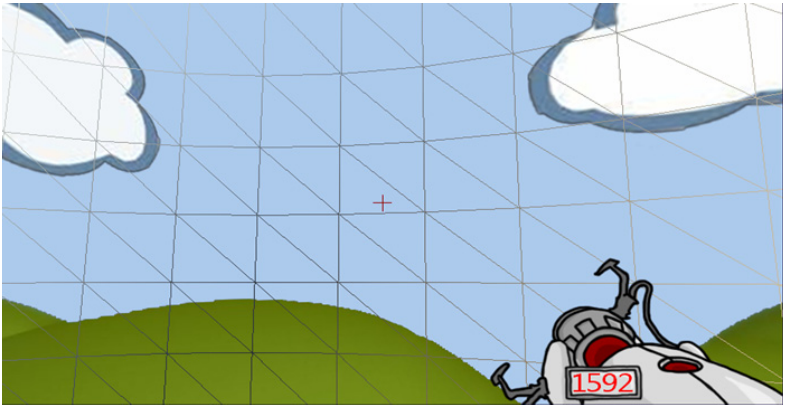

Fig. 2. Gameplay screenshot

randomly or from firing repeatedly at one spot. A drawback, however, is that a balance must be struck between challenging the player to motivate them and preventing them from being able to find solutions. It is not beneficial to us if the players ‘lose’ the game.

3 Evaluation and Results

Using an analysis scheme on data gathered during play-testing (2076 shots taken by 30 players) it was shown that two groups of shots could be identified and that these groups did correspond to directions of re-growth, thus showing that the players were able to locate them within the game environment. The results also suggests that human visual biases, and in part due to the way the Bloch sphere is visualised in-game, players were much more likely to locate re-growth in the horizontal plane than they were in the vertical directions.

Figure 3 shows that players favoured the equatorial re-growth but there are a number of promising shots towards the vertical main solution areas. From [Figure 3(b)] we can identify two antipodal groupings of shots – as mentioned before we know from the work of Wißman et al. that we expect solutions to be orthogonal and hence, on the Bloch sphere, antipodal [21]. As such we may safely select one of the two horizontal groupings visible in [Figure 3(b)] for further analysis. We can also identify a vertical grouping of shots. The groupings that were isolated for further analysis are shown in Figure 4.

In Table 1 (below) μ_{ϕ}^{*} is the weighted mean and σ_{ϕ}^{2} is the variance in the φ direction and μ_{θ}^{*} is the weighted mean and $\sigma_{\theta}^{2}$is the variance in the θ direction. These directions refer to the spherical polar co-ordinates as commonly used in the physical sciences, where θ is the angle to the Cartesian positive z-axis and ϕ is the angle to the Cartesian positive x-axis. Table 1 gives us the vital statistics we require on our player search areas. The final analysis step is to compare the player solution areas to the known areas of regrowth, which are highlighted in Figure 4. This is done using the values in Table 1 as an input to the success metrology function.

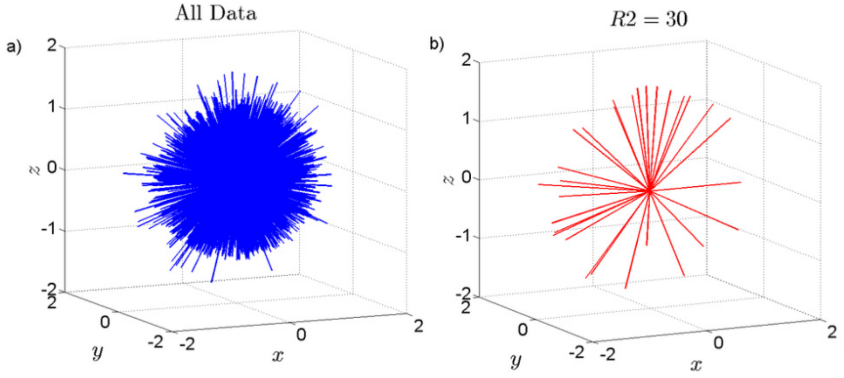

Fig. 3. The quiver plots created by the data sorting function totaling 2076 shots taken by 30 players, and using the parameter R2 = 30. a) All the collected data – 2076 shots. b) The top 30 high-score shots. It can be seen from these plots that players favoured the equatorial solution band over the z-axis solutions, but there are visible groupings both horizontally and vertically.

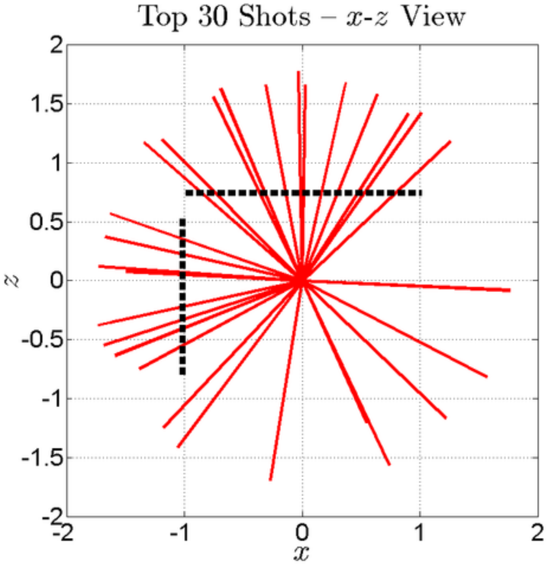

Fig. 4. An x-z plot of the 30 highest scoring shots from the data. Horizontal and Vertical groups which were isolated are indicated with dashed lines.

As this is a prototype game it has been solved and there is a known solution. In order to determine if the game is successful in its aims, it is necessary to compare the player's solution to the known one. The results of this analysis are given below, in Table 2. The known solution was found by direct mathematical analysis of the equations governing the system dynamics. In Table 2, (φ_{known},θ_{known}) is the angular coordinate position of the known solution and σ_{known} defines the radius of the known solution area – this can be set according to what we consider an acceptable search space. In the overlap section of the table the symbols φ and θ refer to the co-ordinate direction through which the player and known solution were convolved and the total overlap is simply the average of the overlap in each co-ordinate direction. It should be noted that the φ_{known} position for the Horizontal group is arbitrary since the horizontal regrowth region is an equatorial band.

Table 1. A table showing the weighted mean position and variance of the player solutions found from the two groups of shots. These parameters will be used to define the player solution areas.

Group	μ_ϕ^*	μ_θ^*	σ_ϕ^2	σ_θ^2
Horizontal	0.02724	1.51617	0.06552	0.06691
Vertical	4.72100	2.67376	2.31627	0.06885

Table 2. The parameters used to define the known solution and the results of the convolution with the player solution. In the Known Solution section of the table, the known solution co-ordinates and standard deviation are shown. In the Overlap section the results of calculating the overlap between the player solution and the known solution are shown.

Group	Known Solution			Overlap			Success?
	ϕ_{known}	θ_{known}	Σ_{known}	ϕ	θ	Total	
Horizontal	0	$\pi/2$	$\pi/18$	0.79362	0.77898	0.78634	Yes!
Vertical	0	0	$\pi/18$	0.09580	0.26022	0.19608	Yes!

It can be clearly seen from Table 2 that the players were much better able to find the equatorial re-growth than the z-axis solutions. There are a few reasons why this might be the case. Firstly, the band solution is a band and obviously larger than the z-axis point solutions so it is easier to find. Secondly, players have a tendency to not actually look directly up or down in game environments, since this is not a natural action in real life. Our normal field of view is ahead and slightly down so players tend top focus their shots in horizontal directions. Finally, the surface of the Bloch sphere is visualised as a grid as can be seen in [Figure 2]; it is quite easy to see the sphere expanding and contracting around the equator as this is represented by a rectangle growing and shrinking, whereas at the poles where the z-axis solutions exist, the expansion and contraction of the sphere is represented by the increasing and decreasing density of converging lines – much harder to interpret visually. One possible solution to this would be to randomly orientate the model with respect to the game environment for each player. Thusly, the z-axis solutions would not always be straight up and down.

Despite these challenges, the results show that players are able to visually identify areas of re-growth within the game environment and that their input could well be useful to research. They have also provided very useful feedback on the game that can be used to improve its design in the future.

4 Conclusion and Future Work

This is valuable feedback for the improvement of the game design. Ultimately it has been shown that players are able to visually identify and locate re-growth and we are able to convert the raw data output of the game into meaningful results, but that changes are needed to counteract player biases and to ensure that players are actively looking for maximal re-growth. The findings are very encouraging and developments envisaged with this feedback will make the game a valuable research tool in the future.

There are many improvements to be made and much work still to be done on this project. First and foremost the collection of more data and the game developer's improvements to the game based on the responses of playtesters are vital to the project. The more data we collect, the more we can tell about how well the game performs from a scientific research standpoint and the results of this data analysis will also be used as feedback for the game developers. One suggested improvement is randomly rotating the axes so that the solutions are in different places for each player. This helps keep the game 'fresh' for each player but also makes them more likely to find the solutions – it means they are more likely to actually be looking for a solution since it will be in a different place every time. Also, in a first-person game such as ours players are more inclined to look around horizontally and angling down than they are to look directly up or down, as in real life these would not be natural actions. Unfortunately, directly up and down (in the z-axis) are currently where our test level solutions exist. We must also investigate how best to make the players actively search for regrowth, rather than simply finding one area of regrowth and firing at it repeatedly or firing randomly in all directions. There is a fine balance to be struck between adding challenges that keep the player moving and motivated to play the game and get a higher score and not making the game so difficult as to detriment the players regrowth-finding abilities. Another point of further work is the development of new levels, with both known and unknown solutions. In terms of improvements to the analysis scheme it is hoped that in the long term identification and isolation of groups of shots will not have to be done manually. One possible scheme is to calculate the shot density function throughout the surface of the sphere and to find maxima in this.

In the longer term we hope the project will be available for many, many more people to play. We hope that the game will prove to be an invaluable research tool in the field of quantum physics but perhaps beyond as well. Points for future investigation include computational complexity theory – comparing the efficiency of the game to the efficiency of current computational techniques. The principal challenge there would be deciding how to define the computational steps of the game in such a way that would be compatible with complexity theory. We also hope to be able to create a roadmap for other scientific GWAPs to follow in much the same way that the creators of Foldit have done, but with relevance to research in quantum physics.

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