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Quantum computer games: quantum minesweeper

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Abstract

The computer game of quantum minesweeper is introduced as a quantum extension of the well-known classical minesweeper. Its main objective is to teach the unique concepts of quantum mechanics in a fun way. Quantum minesweeper demonstrates the effects of superposition, entanglement and their non-local characteristics. While in the classical minesweeper the goal of the game is to discover all the mines laid out on a board without triggering them, in the quantum version there are several classical boards in superposition. The goal is to know the exact quantum state, i.e. the precise layout of all the mines in all the superposed classical boards. The player can perform three types of measurement: a classical measurement that probabilistically collapses the superposition; a quantum interaction-free measurement that can detect a mine without triggering it; and an entanglement measurement that provides non-local information. The application of the concepts taught by quantum minesweeper to one-way quantum computing are also presented.

Introduction

Quantum physics has made a huge impact on the world, from lasers to atomic clocks. Furthermore, the appearance of quantum computers and quantum communication [1] in the near future will introduce a new type of interaction between physics and computer science.

We propose a new type of educational tool, namely, quantum computer games. Note that the term ‘quantum games’ has been associated with quantum game *theory* [2, 3], which is a formal mathematical theory that extends the well-established classical game theory to include quantum strategies. Here we use the term ‘quantum games’ to refer to playing computer games in which the rules of the

game are based on quantum principles, such as superposition, entanglement and the collapse of the wavefunction. Such games can teach the players in an entertaining fashion the basic counter-intuitive logic of the quantum world.

In this article we describe a simple quantum computer game, called quantum minesweeper [4], that is a quantum extension of the well-known minesweeper game. The game board is described by a quantum state which is a superposition of many ‘classical boards’. The player can perform measurements and the goal of the game is to know the exact quantum state.

Quantum minesweeper demonstrates the principles of: (i) superposition, where a certain cell can have a superposition of containing or

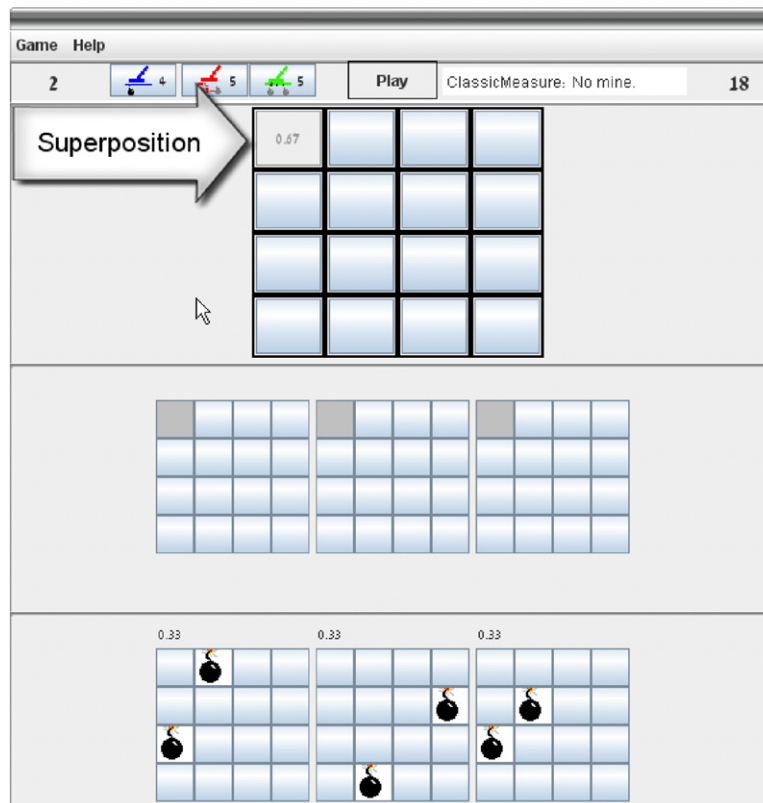


Figure 1. Game board at the end of the first move, a classical measurement of the upper left cell (cell 1), which resulted in a detection of no mine. (Upper board) The player board after the first classical measurement. The information received after the classical measurement of cell 1, $I_1(1)$, is indicated in the cell. (Middle boards) User boards indicating no mine (shaded) in the measured cell. (Lower boards) Solution boards, i.e. the superposition of boards with their probabilities $p_i(1)$ on the top left. Explanation: the information represents the expectation value of the number of adjacent mines, which is, in this example, two mines in three equiprobable boards, $I_1(1) = 2/3$. The non-integer result is the manifestation of a quantum superposition of boards.

not containing a mine; (ii) entanglement and its non-local effects; (iii) the probabilistic nature of a classical measurement and; (iv) a purely quantum measurement, namely interaction-free measurement (IFM) [5]. We elaborate on each of these principles in the next section, accompanied by a specific example illustrated in the figures.

Quantum minesweeper rules

Classical minesweeper is composed of several mines on a rectangular board. The goal is to discover the layout of the mines on the board, without triggering the mines. Quantum minesweeper is composed of a superposition of several classical boards of the same size and number of mines, but with different layouts of the

mines (figure 1 (lower boards)). The goal is to discover all the mine layouts in all the boards, i.e. to know the exact quantum state, without triggering the mines.

In order to do that, the player has several possible moves: (i) perform a classical measurement on a cell; (ii) perform an interaction-free measurement on a cell or; (iii) measure the entanglement of one cell with all others. In addition, similar to the classical minesweeper, whenever the player has perfect knowledge that a certain cell contains (or not) a mine, information concerning adjacent cells is revealed. The player loses if a mine is triggered by a classical measurement or an IFM. The game is won when the player knows and marks all the superposed classical boards, i.e. when the player can perfectly describe the current quantum state.

The initial quantum state is the symmetric superposition of Z random ‘classical boards’, or states, with M mines. The random states selected in the beginning of the game *do not change* during the game, only their respective probabilities, $p_l(t)$, $l = 1, \dots, Z$ (figure 1).

The first available move is to perform a *classical measurement* on a specific cell. The probability of measuring a mine at a specific time t at cell j , $P_j(t)$, is given by the sum of the probabilities of boards having a mine in that cell (figure 1).

The classical measurement has two possible outcomes. The first is finding a mine, whereby it is triggered, the player loses and the game ends, similar to the classical minesweeper. The second outcome is finding there is no mine at that cell, resulting in the collapse of the quantum state to a superposition of the classical boards with no mines in the measured cell.

This simple move demonstrates one of the hallmarks of quantum physics, i.e. an observer is never passive. Performing a measurement not only gives information about the quantum state, it also changes it. The amplitudes of the boards change, and with them the future probabilities of detecting a mine in a specific cell.

Another peculiar property of the quantum world is the *interaction-free measurement* (IFM) [5], whereby one can probabilistically detect a mine without triggering it, by exploiting interferences of quantum probes.

Performing an IFM on cell j has three possible results: (i) triggering the mine, with probability $P_j(t)/2$, thus ending the game, and the player loses; (ii) detecting the mine, without triggering (interacting with) it, with probability $P_j(t)/4$. This results in the collapse of the quantum state to the superposition of boards containing a mine in cell j (figure 2). (iii) With probability $1 - 3P_j(t)/4$, the player does not know if there is a mine or not. The resulting quantum state maintains all its classical boards, but with changed amplitudes, where the relative amplitudes of boards with a mine in cell j are decreased by half.

This unique quantum measurement exploits quantum interferences and can detect the mine, with certain probability, without triggering it (figure 2). While it has been shown that the chance of triggering the mine can be made practically

zero [6, 7], we restrict the application of IFM in quantum minesweeper to the 50% scenario, for obvious entertainment-related reasons.

Furthermore, contrary to the classical measurement, there is a chance that cell j remains in a superposition of containing and not containing a mine. Thus one can perform further measurements on the same cell. However, we have restricted the number of each measurement, to make the game more challenging.

Whenever the player discovers a cell does not contain a mine by using a classical measurement, or contains a mine by using IFM (without triggering it), information concerning adjacent cells is revealed. The information, $I_j(t)$, is displayed in the measured cell, and is the expectation value of the number of mines in adjacent cells (figure 1). This can be viewed either as the sum of probabilities of each adjacent cell to have a mine, or as the sum of adjacent mines in each board, weighted by the board’s probability.

However, contrary to the classical version, this information can change with every following measurement, as measurements collapse the state. Thus, the information displayed is the current information, at each time t , and not the information revealed at the time of the measurement of the cell (figure 2).

To determine the exact quantum state, the player must also measure entanglement. Entanglement is a quantum mechanical property whereby two or more distinct objects have quantum correlations, i.e. measuring one affects the other. These correlations are stronger than classical correlations and are not limited by spatial distance, i.e. even remote quantum objects can be entangled [8].

Quantum minesweeper, by its very nature, facilitates the appearance of entanglement between different cells. This arises from the fact that there is a superposition of many possible ‘boards’ with a fixed number of mines.

This introduces another possible move for the player, namely, *measuring entanglement* between cells. For simplicity, we employ a local measurement of a single cell j , namely measuring an attribute known as linear entropy, denoted by $S_j(t)$ [9]. In quantum minesweeper it assumes the following form:

$$S_j(t) = 2[1 - (P_j(t)^2 + (1 - P_j(t))^2)] \quad (1)$$

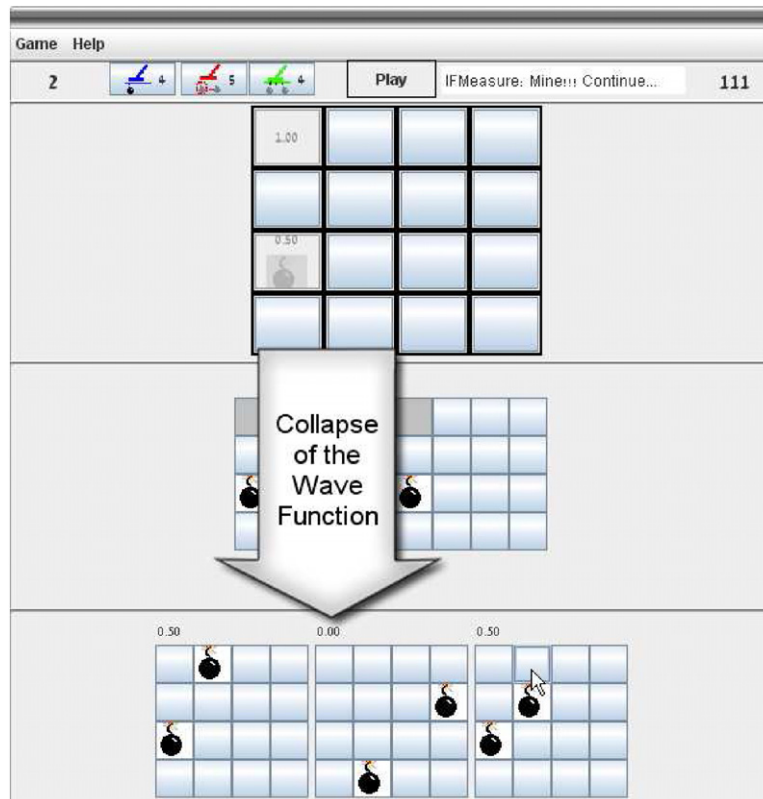


Figure 2. Game board at the end of the second move, an IFM of the left middle cell (cell 9), which resulted in detecting a mine without triggering it. (Upper board) The player board after the IFM. $I_1(2)$ and $I_9(2)$ are indicated in their respective cells. (Middle boards) User boards indicating a detected yet untriggered mine in the measured cell. (Lower boards) Solution boards, i.e. the superposition of boards with their probabilities $p_i(2)$ on the top left. Explanation: the wavefunction, i.e. the quantum state, has collapsed to a superposition of the boards having a mine in the measured cell, namely, the left and right boards, while the centre superposed board's probability has changed to zero, i.e., it is no longer a part of the quantum state. This has resulted in the change of the information in cell 1, $I_1(2) \neq I_1(1)$, a non-local manifestation of quantum entanglement.

where we have introduced a factor of 2 for simplicity so that $0 \leq S_j(t) \leq 1$. Linear entropy gives information about a certain cell that entails a non-local characteristic. If a cell is not entangled with any other cell, the cell is in a 'pure state' resulting in linear entropy equal to zero. An entangled cell is in a 'mixed state' since it is mixed, or entangled, with other cells, resulting in higher linear entropy (figure 3, centre cell).

Linear entropy, similar to the local information of the average number of mines in adjacent cells, may change due to subsequent IFM or classical measurements in distant cells. This may happen due to the change in amplitudes or the collapse of the wavefunction that will result in

the change of the entanglement of the specific cell with other cells.

To win the game, a number of blank boards are used to mark the knowledge the player has on the quantum state (figure 3 (middle boards)). The number of blank boards matches the number of remaining superposed boards and the game is won if the boards have M mines marked with locations consistent with the quantum state.

One-way quantum computation

Quantum minesweeper may help the player understand how quantum computations (QC) work [1]. Most QC implementations are similar in architecture to the classical computer, namely,

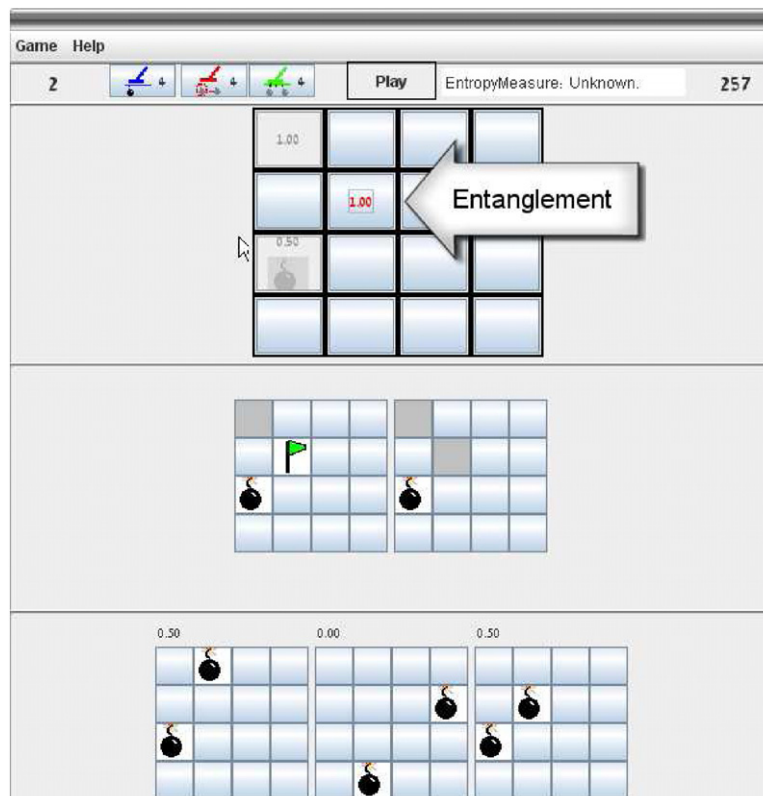


Figure 3. Game board at the end of the last move, linear entropy measurement of a centre cell (cell 6), which resulted in full entanglement measurement. (Upper board) The player board after the linear entropy measurement. $S_6(3)$ is indicated in the measured cell. (Middle boards) The player marked in the user boards the mine not measured by a flag. (Lower boards) Solution boards, i.e. the superposition of boards with their probabilities $p_i(3)$ on the top left. Explanation: the player knows that there is one mine in cell 9 (measured by IFM) and that there is one mine adjacent to cell 1 ($I_1(3) = 1$). The player measured the linear entropy of the middle cell, resulting in $S_2(3) = 1.0$, meaning the cell is fully entangled with another cell, where only the cell above it (cell 2) is an option since $I_9(3) = 0.5$. Hence, one board has a mine in the measured cell and the other board has a mine in cell above it (one ‘quantum’ mine). Thus, with a single classical measurement, a lucky IFM and one linear entropy measurement the player marks the exact superposition of boards, and wins the game.

there is an input, followed by the application of (quantum) logic gates and a read-out of the result in the end. The main differences are that the input state is a superposition of many ‘classical’ inputs and that quantum logic gates introduce entanglement, which is the cornerstone of all quantum information processing. Recently, a new type of quantum computation was introduced [10], namely the one-way quantum computation whereby the initial state is highly entangled, often dubbed cluster state [11], and the computation is performed by a sequence of measurements whose parameters are determined by the previous measurements’ results. This may sound familiar; quantum

minesweeper’s initial state is by its very nature highly entangled and the game proceeds via a sequence of measurements. Hopefully, this will give the player an intuition of how one-way quantum computations work.

Conclusions

The rules of quantum minesweeper as presented in this article follow most of the laws of quantum mechanics. Previous attempts at teaching quantum properties with games have extended tic-tac-toe [12], minigolf [13] and soccer [14]. Each has focused on a specific property of quantum physics.

Quantum minesweeper attempts to convey many of the underlying principles of quantum mechanics in a single game setup. It employs both classical randomness, in the initial selection of the classical boards, and quantum randomness, in the results of the measurements performed by the player. Furthermore, it introduces entanglement that is fully exploited by the player in order to win the game.

Playing quantum minesweeper requires fundamental understanding of probabilities and the consequences of a probabilistic event. Although it is a chance game, it requires the formulation of a strategy in order to maximize the chance of winning, which makes it entertaining and educational.

The game can help the players understand the unique properties that govern the world of quantum mechanics, which are completely counter-intuitive to most people. Furthermore, it may help develop an intuition of what superposition and entanglement mean, and what the benefits of interaction-free measurements are. These newly acquired intuitions can have profound impact on the ability of new players to grasp the quantum world with its myriad of peculiar and fascinating properties.

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