DEPARTMENT OF PHYSICS AND ASTRONOMY

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Quantum Battleships

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Abstract

In this report, we present our version of *Quantum Battleships*, a strategy game that merges classical gameplay with quantum computation. Players can locate enemy ships using both classical and quantum attacks. The quantum shot incorporates Grover's search algorithm, amplifying the probability of finding a ship within a chosen region. The Quantum Zeno effect, also known as the "Watched Pot" effect, acts as a defensive mechanism that protects ships by reducing the impact of quantum attacks through continuous observation. The Elitzur-Vaidman effect is implemented as a scanning tool that detects ships without interacting with them directly. Players are encouraged to combine these strategies to develop effective tactics and discover the optimal path to victory.

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1 Introduction

Here we will lay out some of the mechanics behind the game and some of the theory behind the individual algorithms.

1.1 Grover Circuit Implementation and Analysis

Figure 1 illustrates a quantum circuit implementing Grover's search algorithm for a two-qubit system with the oracle state $|10\rangle$. The circuit can be divided into two steps: the *oracle* and the *diffusion operator*, each responsible for a key step in the amplitude amplification process. The boxed section in the figure highlights the repeating segment of the algorithm that constitutes one full iteration of the Grover operator.

Oracle Construction

The oracle U_ω is a unitary operation that identifies the target state by inverting its phase while leaving all other basis states unchanged. In this case, the oracle marks $|10\rangle$ by applying a controlled-Z operation embedded within a series of single-qubit transformations

$$U_\omega = \hat{X}\hat{H}(CNOT)\hat{H}\hat{X}.$$

The initial pair of $\hat{X}$ and $\hat{H}$ gates prepare the control qubit such that the subsequent controlled-Z (realized via $CNOT$) applies a phase flip specifically when the qubit register corresponds to $|10\rangle$. The final $\hat{H}\hat{X}$ sequence restores the computational basis. Physically, this operation corresponds to "marking" the battleship location in our quantum version of the game, without yet performing any measurement.

Diffusion Operator

Following the oracle, the *diffusion operator* is applied to amplify the probability amplitude of the marked state. Mathematically, this operator is given by

$$U_s = 2|s\rangle\langle s| - I = H^{\otimes n}(2|0\rangle\langle 0| - I)H^{\otimes n}.$$

In the circuit, this is implemented through a sequence of Hadamard and Pauli-X gates that map $|s\rangle$ to $|0\rangle^{\otimes n}$, performing a phase inversion on $|0\rangle^{\otimes n}$ using a multi-controlled Z, and then reversing that mapping. Conceptually, this operation reflects all amplitudes about their mean value, boosting the probability of the oracle-marked state while diminishing all others.

Grover Iteration and Looping Mechanism

Each complete iteration of Grover's search consists of applying the oracle U_ω followed by the diffusion operator U_s. Repeating this sequence $R \approx \frac{\pi}{4}\sqrt{N}$ times optimises the number of grover iterations needed to maximise the amplitude of the target state, ensuring that a measurement is highly likely to yield the correct result.

In Qiskit, this looping behaviour can be done by using subcircuits that encapsulates both the oracle and diffusion stages. For small systems such as a 2×2 region ($N = 4$), a single iteration suffices to achieve near-perfect probability amplification.

1.2 Elitzur–Vaidman Effect

The Elitzur–Vaidman (EV) effect demonstrates the principle of interaction–free measurement, where the presence of an object can be inferred without any direct physical interaction between the measuring system and the object itself. The canonical example is the "quantum bomb tester", which employs a single photon inside a Mach–Zehnder interferometer to determine whether a light–sensitive bomb is live or a dud.

Qiskit Circuit Representation

The Elitzur–Vaidman interferometer can be naturally expressed as a two–qubit quantum circuit. The first qubit represents the photon path within the interferometer, encoding whether the photon travels along the upper or lower arm, while the second qubit represents the bomb or ship state, which determines whether interaction is possible.

The first operation applied to the photon qubit is a Hadamard gate, corresponding to the initial beam splitter. This transforms the input state $|0\rangle$ into an equal superposition of both paths

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle),$$

representing the photon being simultaneously in the upper and lower arms of the interferometer.

If a live bomb (or ship) is present in one path, its potential to interact with the photon is modelled by a controlled–Z (`CZ`) gate. This gate applies a π phase shift to the joint state $|11\rangle$, corresponding to a photon travelling along the lower arm while a live bomb is present. Mathematically, the controlled–Z acts as

$$U_{CZ} = \mathrm{diag}(1,\, 1,\, 1,\, -1),$$

introducing a relative phase between the two possible photon paths. This operation destroys the perfect interference that would otherwise occur between the upper and lower components of the superposition.

A second Hadamard gate is then applied to the photon qubit, representing the second beam splitter where the two paths recombine. In the absence of a bomb, the two path amplitudes interfere constructively at the bright output port, yielding the deterministic measurement outcome $|0\rangle$. When a bomb is present, however, the introduced phase shift removes the interference condition, producing an equal probability of detecting $|0\rangle$ or $|1\rangle$.

Finally, measurement of the photon qubit corresponds to observing at which output port the photon exits. A detection in $|1\rangle$ (the "dark port") signifies the presence of a live bomb or ship, representing an interaction free detection, because the photon never actually interacted

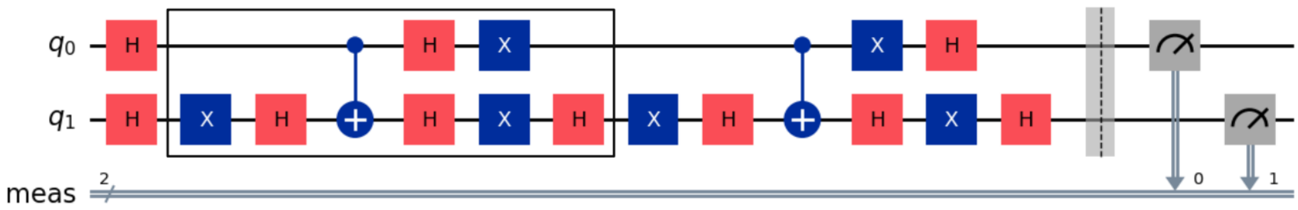

Figure 1: Grover algorithm for a two qubit system with oracle $|10\rangle$. The box shows the two functions the oracle $(\hat{X}\hat{H}(CNOT)\hat{H}\hat{X})$ for the key state $|10\rangle$ and the diffuser $(\hat{H}\hat{X}\hat{H})$ [This image was generated using qc.draw("mpl") using QISKIT].

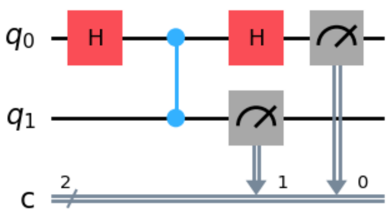

Figure 2: Elitzur–Vaidman bomb tester circuit. A two-qubit Qiskit implementation where the photon (top qubit) passes through two beam splitters (Hadamard gates) and interacts with the bomb (bottom qubit) via a controlled operation. Measuring $|1\rangle_{\text{photon}}|0\rangle_{\text{bomb}}$ indicates an interaction-free detection of a live bomb.

with the object. The complete Qiskit implementation of this process is shown in Figure 2.

1.3 Zeno Defence mechanism

The Quantum Zeno effect illustrates one of the most counterintuitive aspects of quantum mechanics: a system's evolution can be inhibited through frequent observation. Repeated measurement effectively "freezes" the quantum state, preventing transitions that would otherwise occur under unitary evolution. This phenomenon arises from the non-unitary nature of measurement, which projects the system back into its initial eigenstate, continually interrupting the natural Schrödinger evolution.

Physical Principle

Consider a single qubit initially prepared in the state $|0\rangle$, representing a ship in its fully protected configuration. In the absence of measurement, a unitary evolution such as a small rotation about the y-axis,

$$U(\delta t) = e^{-i\theta\sigma_y/2},$$

would gradually rotate the state toward $|1\rangle$, corresponding to an increased probability of detection by an enemy quantum weapon. However, if the system is subjected to repeated projective measurements in the $\{|0\rangle, |1\rangle\}$ basis after each infinitesimal time interval δt, the cumulative probability of leaving $|0\rangle$ is suppressed as

$$P_{\text{survival}}(t, n) = \left[\cos^2\left(\frac{\theta}{2n}\right)\right]^n \approx e^{-\theta^2/(4n)}.$$

In the limit of infinitely frequent measurements ($n \to \infty$), the survival probability tends to unity, implying that continuous observation perfectly inhibits evolution, the essence of the Quantum Zeno effect.

Circuit Construction in Qiskit

Figure 3 shows the single-qubit circuit used to implement the Zeno Defence mechanism. The circuit begins with a Hadamard gate, preparing the qubit in a balanced superposition

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle).$$

Subsequent pairs of rotation gates simulate the interplay between quantum evolution and measurement. Each protection cycle consists of a small forward rotation $R_y(0.2)$ representing natural decoherence or enemy probing, followed by a partial counter-rotation $R_y(-0.1)$ modelling a weak measurement that restores the qubit closer to its original state. The cumulative effect of these cycles is to restrict the qubit's motion on the Bloch sphere, confining it near the north pole ($|0\rangle$). The number of cycles determines the protection strength: more frequent corrections yield higher survival probabilities.

After three such cycles, the final measurement determines whether the ship remains protected ($|0\rangle$) or has partially evolved toward detectability ($|1\rangle$). In simulation, outcomes of $|0\rangle$ correspond to a *maximum protection state* (approximately 90% immunity to quantum attacks), while outcomes of $|1\rangle$ indicate *partial protection* (roughly 60% efficacy).

2 Rules of the Game

2.1 Game Modes

Players can select between two distinct modes from the main menu:

- **Single Player:** Play against an AI opponent with adjustable difficulty levels.
- **Local Multiplayer:** Two players take turns on the same computer.

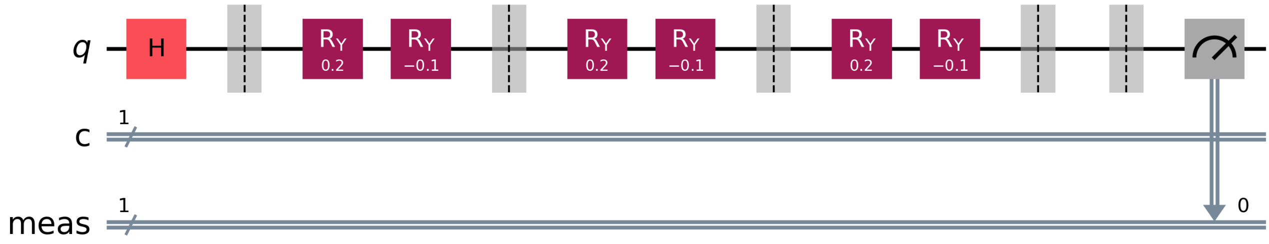

Figure 3: Quantum Zeno Defence circuit. A single-qubit implementation in Qiskit where repeated weak rotations and partial corrections emulate the effect of continuous observation, suppressing the qubit's evolution from the protected state $|0\rangle$ to the vulnerable state $|1\rangle$.

2.2 Setup Phase

Ship Placement Each player places eight ships on their 8×8 grid. Ships can be positioned manually by clicking individual squares or automatically by selecting the *Random Ships* option. Once satisfied, players confirm placement by clicking *Ready for Battle*.

Turn Structure Players alternate turns, with each turn allowing a single action. Strategic planning and resource management are key to success.

2.3 Battle Phase

Targeting Modes

Before each attack, players select a targeting pattern:

- **Classical:** Targets a single square (1×1).
- **2×2 Grid:** Targets a quantum region (2×2).
- **Full Row:** Targets an entire horizontal row.
- **Full Column:** Targets an entire vertical column.

2.4 Quantum Weapons

Grover Shot **Targeting:** Option to choose a 2×2 region/full row or column. **Effect:** High probability of hitting when ships are present in the region.

EV Scan **Targeting:** Option to choose a 2×2 region/-full row or column. **Effect:** Detects the presence of ships without damaging them. **Results:**

- *Clear:* No ships detected (high confidence).
- *Detected:* One or more ships present within the scanned region.
- *Interaction:* Ships slightly disturbed but not destroyed.
- *Inconclusive:* Quantum interference prevented a clear reading.

Zeno Defence **Targeting:** Selects individual squares on the player's own grid. **Effect:** Shields ships from quantum attacks using the Quantum Zeno Effect. **Duration:** One round per activation. **Effectiveness:** Provides 90% (maximum) or 60% (partial) protection depending on defense strength.

Classical Shot **Targeting:** Single square selection. **Effect:** Standard battleships mechanics. **Strategy:** Reliable and simple, but limited to a single cell per turn.

2.5 Winning Conditions

Victory: Achieved when all enemy ships are destroyed. **Strategy:** Success requires balancing offensive and defensive tactics, predicting enemy moves, and managing limited quantum resources effectively.

3 Incorporation into the Game

The *Quantum Battleships* game integrates three fundamental quantum effects, the Elitzur–Vaidman (EV) interaction-free measurement, Grover's quantum search, and the Quantum Zeno effect, into a turn-based strategy environment. The player operates on a grid representing possible ship positions, each cell corresponding to a computational basis state of the quantum system.

Game Setup Upon starting the game, the player is presented with an $N \times N$ grid of possible ship locations. Ships are hidden at random coordinates, each encoded as a basis state $|x_i\rangle$. The number of qubits required for representation is determined by $n = \lceil \log_2 N^2 \rceil$, defining the Hilbert space over which the search and measurement operations occur. The interface displays the grid as a quantum ocean, with selectable regions corresponding to subsets of basis states.

EV Scan The first action available to the player is the EV Scan, inspired by the Elitzur–Vaidman bomb tester experiment. When a player performs an EV Scan over a selected region, the game runs a quantum circuit that checks whether the normal pattern of quantum interference has been disturbed. If the pattern remains unchanged, the region is empty. But if the interference breaks down, it means there is at least one ship in that area, even though the scan never directly interacts with it. In this way, the EV Scan allows the player to detect a ship's presence without revealing or damaging it.

Grover Shot The player may execute a *Grover Shot*. This operation applies Grover's search algorithm over the selected region to amplify the probability amplitude of marked (ship) states. Measuring the resulting quantum state simulates firing at the most probable location. A successful hit corresponds to measuring a basis state matching a ship position, collapsing that part of the wavefunction and revealing the ship on the grid.

Zeno Defence To counter attacks, the defending player can activate Quantum Zeno Defense. This feature exploits the Quantum Zeno effect, repeated weak measurements that inhibit state evolution. By applying controlled dephasing or frequent projective operations to selected cells, the defender effectively "freezes" those positions, reducing the likelihood that a Grover search will amplify their amplitudes. In gameplay terms, Zeno-protected cells become more resistant to detection or destruction, acting as a form of quantum shielding.

Game Progression Each turn consists of choosing between scanning (EV), attacking (Grover), or defending (Zeno). The quantum circuits corresponding to these actions are executed on a simulator backend, with results determining the visual updates on the grid. The game continues until all ships are located, destroyed, or shielded. The probabilistic nature of measurement ensures that each match evolves differently, highlighting the interplay between quantum interference, amplitude amplification, and decoherence as strategic tools within the same interactive system.

4 Further improvements

The first major improvement we would introduce to the game is adding length and width to the ships, similar to the mechanics of the original Battleship game. Currently, all ships in our version occupy a single unit on the grid, which results in a gameplay experience that is more reliant on guessing rather than strategy. By giving ships a defined size (e.g., spanning multiple cells in length or width), players would need to use more logical deduction and positional reasoning to locate and sink enemy ships. This change would make the game not only more engaging but also more faithful to the strategic roots of the original Battleship.

A second improvement would focus on the user interface. While the current interface is functional, it remains somewhat rough around the edges, primarily due to the time constraints of our one-week development window. With more time, we would aim to design a cleaner, more intuitive, and appealing interface that enhances the overall player experience. This could include smoother animations, improved grid visualization, better feedback on hits and misses, and a more immersive way to represent quantum effects and weapon usage. A refined UI would help players understand complex mechanics more naturally and make the game feel more polished and professional.

Another improvement that would have helped the players entails adding a rule/demo explaining the game functionality with brief explanations about how each move works.

Finally, an especially intriguing improvement we had but did not have time to implement is the idea of entangled ships. This mechanic would link two ships such that actions performed on one ship could influence the state of another. For example, a hit on one entangled ship might partially reveal, or protect its partner ship, depending on how the entanglement is modelled. This would introduce a fascinating layer of quantum unpredictability and interconnected strategy, pushing players to think about how quantum phenomena could influence traditional gameplay dynamics.

5 Conclusion

The development of Quantum Battleships demonstrates how quantum mechanical principles can be translated into accessible, gameplay. By incorporating Grover's search algorithm, the Elitzur-Vaidman effect, and the Quantum Zeno effect, the game allows players to engage directly with three distinct quantum phenomena: superposition, interference, and measurement induced state control, without requiring prior expertise in quantum computing.

Each mechanic plays a complementary role: the Grover Shot embodies quantum search and probability amplification, the EV Scan introduces non destructive detection through interference, and the Zeno Defence highlights the stabilising power of frequent measurement.

6 Remark

Note that we have created a fully working quantum battleship game with visuals/UI. Note that there was lots of AI help when it came to write UI and frontend functionality for the game, however implementation of algorithms/-circuits was done by us. Further information can be found on the following team member's Github repositories:

- View Original Repo by Adam
- Forked Repo by Yann
- Qasim's Github

Appendices: WORK IN PROGRESS...

A Appendix A: Grover's algorithm

This appendix contains a mathematical framework behind Grover's algorithm. First, take some initial system with a state composed of n 0 qubits, $|\psi_0\rangle = |0\rangle^{\otimes n}$. This system undergoes a Hadamard transformation, creating a superposition of

leave this for l8r $\lfloor R \rfloor = \frac{\pi}{4 \arcsin\left(\frac{1}{N}\right) - \frac{1}{2}}$

B Appendix B: Mach–Zehnder Interferometer

In a Mach–Zehnder interferometer, a single photon enters the system and encounters a half–silvered mirror acting as a 50/50 beam splitter. This is represented by a Hadamard transformation,

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix},$$

which places the photon into an equal superposition of the upper and lower interferometer arms,

$$|\psi_1\rangle = H|0\rangle = \frac{1}{\sqrt{2}} (|u\rangle + |\ell\rangle).$$

Each path then accumulates a relative phase during propagation. If no obstacle is present, the two paths recombine coherently at the second beam splitter, which is also described by H. The resulting output state is

$$|\psi_2\rangle = H|\psi_1\rangle = H^2|0\rangle = |0\rangle,$$

so that the photon always exits through the "bright" port and never through the "dark" one, corresponding to complete constructive and destructive interference, respectively.

If, however, a live bomb is placed in the lower arm, it acts as a measurement device that absorbs any photon travelling along that path. This measurement is described by a projective operator

$$P = |\ell\rangle\langle\ell|, \qquad Q = I - P = |u\rangle\langle u|,$$

which removes coherence between the two arms of the interferometer. The density matrix of the photon after encountering the bomb becomes

$$\rho' = P\rho P + Q\rho Q,$$

eliminating the off–diagonal interference terms. When the surviving amplitude from the upper path reaches the second beam splitter, the photon has a 50% chance of being detected at either output port. Thus, if a photon is observed at the normally dark detector, one infers the presence of a live bomb—even though no absorption (and hence no "explosion") occurred. This is the essence of *interaction–free measurement*.