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QUANTUM PORT: GAMIFICATION OF QUANTUM TELEPORTATION FOR PUBLIC ENGAGEMENT

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Abstract Concepts on quantum physics are generally difficult for the general public to understand and grasp due to its counter-intuitive nature and requirement for a higher level of mathematical literacy. With categorical quantum mechanics (CQM), quantum theory is re-formalized into a more intuitive diagrammatic approach, which we will refer to as the first level of transformation, to improve the accessibility and readability of quantum theory to a broader audience since the mathematical details are embedded into diagrammatic rules. Taking inspiration from this diagrammatic approach, we propose the second level of transformation by gamifying the diagrammatic rules of quantum teleportation into a quantum card game called Quantum Port. In this work, we discuss the gamification process of quantum teleportation and provide a printable version of Quantum Port for public engagement.

Key words categorical quantum mechanics; gamification; quantum teleportation; quantum port

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1 Introduction

Since the inception of quantum theory through wave and matrix formalisms by Schrödinger[1] and Heisenberg[2], independently and respectively, quantum theory has contributed to the fundamental understanding of our physical world and will continue to be an integral part of modern technologies through the second quantum revolution[3]. On 7 June 2024, the United Nations (UN) proclaimed 2025 to be the International Year of Quantum Science and Technology (IYQ 2025) to celebrate and recognize the importance of quantum theory to humanity[4], particularly with the recent breakthroughs of quantum computing[5,6] which may help to realize the possibility of using quantum machine learning and artificial intelligence for the benefit of humanity at large[7-10].

However, quantum theory remains a difficult subject for the general public to understand, especially for those without formal training in physics and mathematics.

This is due to the counter-intuitive nature of fundamental concepts in quantum theory, such as quantum entanglement[11] and quantum contextuality[12,13]. With the recent announcement on the Willow quantum chip that demonstrated the possibility of real-time quantum error correcting[6], we may soon enter the age of fault-tolerant quantum computing[14]. Hence, it is important to improve quantum literacy among the general public so that quantum theory becomes more accessible to non-specialists. In order to achieve this goal, various teaching and learning mod-

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ules[15-21] and quantum games[22-29] have been proposed to engage audiences of varying levels of backgrounds, so that the quantum ecosystem will be more inclusive than just quantum scientists, researchers, and technology companies. In this paper, we describe a quantum card game based on quantum teleportation, called Quantum Port, that features two levels of transformation. The first level of transformation comes from the diagrammatic approach to quantum theory[30], whereas the second level of transformation comes from the gamification of the diagrammatic rules to quantum teleportation.

Our paper will be divided into the following sections. In Section 2, we will briefly describe the mathematical formalism and the protocol of quantum teleportation. In Section 3, we will explain how a picture of quantum teleportation is derived in the diagrammatic approach of categorical quantum mechanics. In Section 4, we will introduce the Quantum Port card game and discuss the gamification process. We conclude our work with some future prospects for the current version of Quantum Port.

2 Quantum teleportation

Quantum teleportation[31] begins with two parties, Alice and Bob, sharing a pair of entangled qubits in one of the Bell bases,

$$|\Phi\rangle_{AB}^{+}=\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) \tag{1}$$

$$|\Phi\rangle_{AB}^{-}=\frac{1}{\sqrt{2}}(|00\rangle-|11\rangle) \tag{2}$$

$$|\Psi\rangle_{AB}^{+}=\frac{1}{\sqrt{2}}(|01\rangle+|10\rangle) \tag{3}$$

$$|\Psi\rangle_{AB}^{-}=\frac{1}{\sqrt{2}}(|01\rangle-|10\rangle) \tag{4}$$

Without loss of generality, we focus on the Bell basis $|\Phi\rangle_{AB}^{+}$ in our discussion. The other Bell bases follow the same mathematical arguments, and the Pauli correction required for each of the Bell bases will be summarized in Table 1.

Table 1 Pauli correction (in term of σ_i, $i=1,2,3,4$) up to a global phase equivalence on Bob's qubit to obtain the correct quantum information

	00	01	10	11
$\|\Psi\rangle_{AB}^{+}$	σ_1	σ_4	σ_2	σ_3
$\|\Psi\rangle_{AB}^{-}$	σ_2	σ_3	σ_1	σ_4
$\|\Phi\rangle_{AB}^{+}$	σ_4	σ_1	σ_3	σ_2
$\|\Phi\rangle_{AB}^{-}$	σ_3	σ_2	σ_4	σ_1

Alice has a third qubit, $|\psi\rangle_C=\alpha\ |0\rangle+\beta|1\rangle$ that she wants to send to Bob. Instead of sending the qubit $|\psi\rangle_C$ directly to Bob, she can utilize the Bell pair and the assistance of classical communication to achieve the same task in a more secure way. The protocol for quantum teleportation is illustrated in Fig. 1.

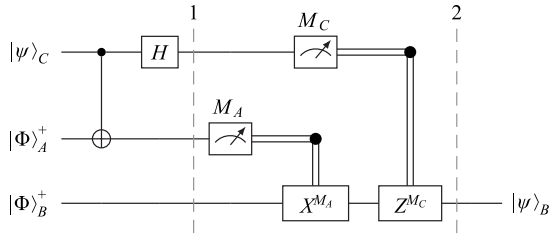


Fig. 1 Quantum teleportation

Initially, the shared Bell state between Alice and Bob, and the qubit that Alice wants to send to Bob are given as

$$|\psi\rangle_{CAB}=(\alpha|0\rangle_C+\beta|1\rangle_C)\otimes\frac{1}{\sqrt{2}}(|00\rangle_{AB}+|11\rangle_{AB})$$

$$=\frac{1}{\sqrt{2}}(\alpha|000\rangle+\alpha|011\rangle+\beta|100\rangle+\beta|111\rangle) \tag{5}$$

After the CNOT gate, the above quantum state becomes:

$$\psi\rangle_{CAB}=\frac{1}{\sqrt{2}}(\alpha|000\rangle+\alpha|011\rangle+\beta|110\rangle+\beta|101\rangle) \tag{6}$$

After the Hadamard gate, the quantum state at Step 1 in Fig. 1 will become:

$$|\psi\rangle_{CAB}=\frac{1}{\sqrt{2}}\left[\frac{\alpha}{\sqrt{2}}(|0\rangle_C+|1\rangle_C)\otimes|00\rangle_{AB}+\right.$$

$$\left.\frac{\alpha}{\sqrt{2}}(|0\rangle_C+|1\rangle_C)\otimes|11\rangle_{AB}+\right.$$

$$\frac{\beta}{\sqrt{2}}(|0\rangle C-|1\rangle_C)\otimes|10\rangle_{AB}+$$
$$\frac{\beta}{\sqrt{2}}(|0\rangle C-|1\rangle_C)\otimes|01\rangle_{AB}\Big]$$
$$=\frac{1}{2}[\alpha|000\rangle+\alpha|100\rangle+\alpha|011\rangle+$$
$$\alpha|111\rangle+\beta|010\rangle-\beta|110\rangle+$$
$$\beta|001\rangle-\beta|101\rangle]$$
$$=\frac{1}{2}[|00\rangle_{CA}(\alpha|0\rangle_B+\beta|1\rangle_B)+$$
$$|01\rangle_{CA}(\beta|0\rangle_B+\alpha|1\rangle_B)+$$
$$|10\rangle_{CA}(\alpha|0\rangle B-\beta|1\rangle_B)+$$
$$|11\rangle_{CA}(-\beta|0\rangle_B+\alpha|1\rangle_B)] \quad (7)$$

In Step 2, quantum measurements will be performed on Alice's qubits (qubit A and C) and the appropriate Pauli correction will be applied to Bob's qubit (qubit B) to recover the quantum information that is teleported. In short,

(1) If the quantum measurement results in $|00\rangle_{CA}$, nothing $\left(\sigma_4=\begin{pmatrix}1&0\\0&1\end{pmatrix}\right)$ will be performed;

(2) If the quantum measurement results in $|01\rangle_{CA}$, Pauli X, $\sigma_1=\begin{pmatrix}0&1\\1&0\end{pmatrix}$ will be performed;

(3) If the quantum measurement results in $|10\rangle_{CA}$, Pauli Z, $\sigma_3=\begin{pmatrix}1&0\\0&-1\end{pmatrix}$ will be performed;

(4) If the quantum measurement results in $|11\rangle_{CA}$, Pauli Y up to a global phase of i, $i\sigma_2=\begin{pmatrix}0&1\\-1&0\end{pmatrix}$ will be performed.

One may repeat the same calculation as above for other Bell bases and obtain the results shown in Table 1.

3 First level of transformation: Diagrammatic approach to quantum processes

Categorical Quantum Mechanics (CQM) is a diagrammatic approach to quantum theory that was introduced by Abramsky and Coecke[32]. The motivation for CQM is to find a generalized framework for quantum theory, with category theory as its mathematical backbone, and refine it until we can find a complete description of quantum mechanics. In the years since the introduction of CQM, Coecke and his many collaborators have refined CQM to include descriptions of mixed states and purification[33-35], quantum measurement and observables[36-38], quantum and classical channels[35,39], and causal structures[40,41]. This section follows closely the derivation of quantum teleportation in the highly accessible textbook by Bob Coecke and Aleks Kissinger on CQM[30].

The basic building blocks of CQM are processes, depicted as a trapezoid with an incoming wire and outgoing wire. In this section, we adopt the bottom-to-top convention of reading a diagram. So, the incoming wire is at the bottom and the outgoing wire is at the top. These wires represent finite-dimensional quantum systems.

Processes obey certain rules that allow for the box in a process to move along its wires. The composition of processes is itself a process and can be represented as multiple diagrams, as depicted in Fig. 2. Figure 2 also shows that processes can be composed sequentially and in parallel.

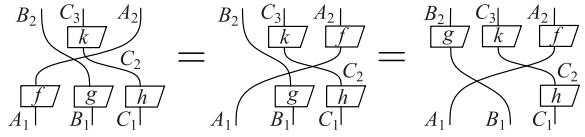


Fig. 2 A composition of processes and its equivalent diagrams

A state ψ of a system A is a process without an input wire (see Fig. 3). In contrast, an effect ϕ of a system A is a process without an output wire (see Fig. 4).



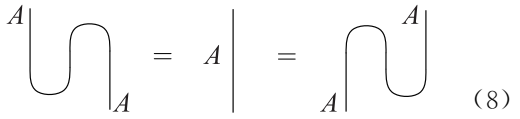
Fig. 3 State ψ of system A



Fig. 4 Effect ϕ of system A

CQM treats entanglement as fundamental to quantum theory. It is required for every system,

say A, to have a non-separable bipartite state, called cup (see Fig. 5), and a non-separable bipartite effect, called cap (see Fig. 6), which satisfy Equation 8.

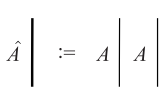


(8)



Fig. 5 Cup for system A Fig. 6 Cap for system A

To simplify a diagram—so that we do not need to draw a process twice in a single diagram—we can apply the "doubling" convention introduced by Coecke. The doubling of a wire is shown in Fig. 7 and the doubling of a process is shown in Fig. 8. The doubling convention allows for the inclusion of quantum states and operations which are not necessarily pure. These are the processes in the "double world" which do not have a single counterpart, i. e. they cannot be redrawn as the (separable) parallel composition of a single process and its conjugate.



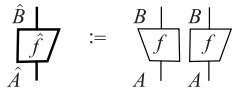


Fig. 7 Double wire for system A Fig. 8 Double process for process f

Henceforth, we shall use the "doubling" convention and denote them by their single counterpart with the hat symbol. For those double diagrams that may not have a single counterpart, we shall label them without the hat symbol. Furthermore, we shall forego labeling the wires henceforth. Unless otherwise stated, each diagram will involve only systems of the same dimension. That is, a diagram will not have a system with dimension d_1 and a system with dimension d_2 where $d_1 = d_2$. At this point, we have introduced the diagrams needed to provide a picture of quantum teleportation.

In Fig. 9, the wires in the diagram are qubits. The state $\hat{\psi}$ is the state that Alice needs to send to Bob. The cup in Step 1 is the shared Bell state between Alice and Bob. The cap in Step 2 is the measurement Alice performs on her part of the Bell state and $\hat{\psi}$, where the process $\hat{P}_i$ is the Pauli matrix that represents the measurement outcome obtained by Alice. Finally, in Step 3 on Bob's side, Bob applies the Pauli correction needed to obtain $\hat{\psi}$, so it must be equal to the Pauli matrix in Step 2. We can simplify the diagram for quantum teleportation in the following way:

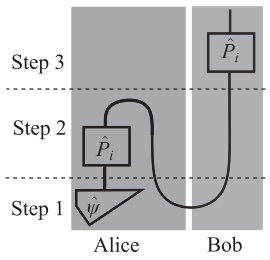
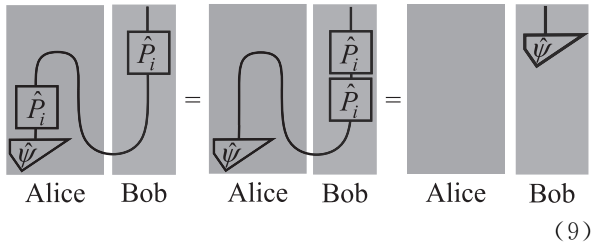


Fig. 9 A first picture of quantum teleportation



(9)

In Equation (9), the $\hat{P}_i$ on Alice's side is slid along the wire to Bob's side in the first equality, and the second equality is due to Equation 8 and the self-unitarity of the Pauli matrix in the diagram.

The picture of quantum teleportation in Fig. 9 can be generalized so that the wires represent (double) qudits with $d \geqslant 2$. Then, the set of $\hat{P}_i$ can be replaced with a set of unitaries $\hat{U}_i$, while $\hat{\psi}$ can be replaced with a state not necesarily pure, say ρ. This is shown in Fig. 10, where the unitaries are indexed to represent the outcomes of the measurement performed by Alice, and the dashed line encompasses this measurement.

The diagram in Fig. 10 is a post-measurement picture of quantum teleportation. That is,

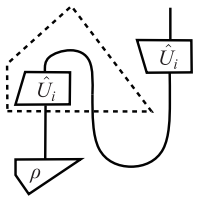


Fig. 10 The general post-measurement diagram for quantum teleportation

there is an implicit assumption that Alice communicates the outcome of her measurement to Bob by the matching index i of the unitaries. If Alice does not communicate her measurement's outcome, the state ρ cannot be transported to Bob but instead, Bob receives a maximally mixed state. Alice needs to communicate the outcome of her measurement to Bob and this communication is classical.

While the doubling convention is certainly convenient, there is a structural reason behind its introduction, namely, to distinguish quantum systems from classical systems, where quantum systems are double wires while classical systems are single wires. A classical system is a system encoded with classical values via a fixed orthonormal basis. Indeed, when we do an experiment in a quantum system, the results that we observe from the experiment are recorded as classical data-information that we can read.

Again, we take the example of quantum teleportation, where the possible outcomes of Alice's measurement are given by an orthonormal basis. The interaction between quantum and classical systems is depicted by two processes: Encode, which has a single wire as its input and a double wire as its output, as shown in Fig. 11; and Measure, which has a double wire as its input and a single wire as its output, as shown in Fig. 12. Their names give a hint on how they are interpreted in quantum theory, i. e. encode is the process of encoding classical data into a quantum system, whereas measure is the process of extracting classical data from a quantum system.



Fig. 11 The encode process, which has a single wire as its input and a double wire as its output



Fig. 12 The measure process which has a double wire as its input and a single wire as its output

Now that we have a way to describe a quantum-classical interaction, we can complete our picture of quantum teleportation, which includes a classical communication between Alice and Bob, as shown in Fig. 13. The unitary process in the diagram has become a controlled unitary as its application by Bob depends on the outcome of the measurement performed by Alice. That is, Alice extracts classical data through measurement on the state of the bipartite system on her side. She then sends the aforementioned data to Bob and Bob encodes the classical data into the quantum system on his side. We can rewrite the diagram in a similar manner to Equation 9 to show that the quantum state ρ is indeed transported successfully from Alice to Bob.

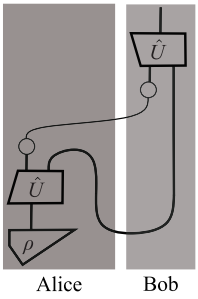


Fig. 13 A picture of quantum teleportation with classical communication

4 Second level of transformation: Gamification

The second level of transformation comes from the gamification of the diagrammatic rules to quantum teleportation. Before we begin, we would like to clarify that all in-game terminologies will be capitalized and in the typewriter font.

4.1 Introduction to in-game components and terminologies

Quantum Port is a tabletop game played by

two players. At the beginning of the game, each player is given a deck of 41 cards, consisting of Circuit Cards and Action Cards; 4 Quantum Data Coins (QDC), 4 Classical Data Coins (CDC), and a Classical Coin. In addition to the cards and coins, a Four-Sided Die should be included in a complete set.

The Circuit Cards are further divided into the Classical Circuits (illustrated with thin, white lines), Quantum Circuits (illustrated with thick, black lines), Swap Circuits (a mixture of Classical and/or Quantum Circuits), Entangler, and Pauli Correction. Meanwhile, there are four types of Action Cards, namely Information Jammer, Circuit Destroyer, Information Revealer, and Eavesdropper.

The Data Coins have symbols on them. A QDC has its tail (also known as coin back or reverse) "Q" and head (also known as coin front or obverse) being one of the following symbols: "Ψ^+", "Ψ^-", "Φ^+", and "Φ^-". Meanwhile, a CDC has its tail "C" and head being one of the following symbols: "00", "01", "10", and "11". A Classical Coin has "C" on both its head and tail.

4.2 Setups and winning conditions

To set up the game, each player performs the following procedures.

(1) Choose some QDC: 1 QDC for the Beginner setup, 2 QDC for the Default setup;

(2) Shuffle their deck of cards and pick 4 from the top of the deck;

(3) Place the chosen QDC on the player's left with the head facing down, along with their Classical Coin in a vertical alignment (refer to Figs. 14 and 15 for Beginner and Default setups respectively). The locations of QDC and Classical Coin determine how to build the Quantum Teleportation Circuit (QTC) later on.

In the Beginner setup, the fastest player to obtain a QDC wins the game. In the Default setup, the player who holds the most QDC on hand at the end of the game will win. There are two ways for a player to obtain a QDC.

Aim 1 Complete a QTC and execute an instance of quantum teleportation;

Aim 2 Steal a QDC while the opponent attempts to execute an instance of quantum teleportation.

4.3 Eligible Turns and Moves

Each player takes Turns to perform Moves in order to obtain a QDC. In each Turn, a player is limited to two Moves. A Move consists of either one of the following.

(1) Use a Circuit Card to build their QTC;

(2) Discard a Circuit Card in their QTC;

(3) Draw a card from their deck;

(4) Use an Action Card to sabotage their opponent;

(5) Roll the Four-Sided Die to decide the corresponding CDC to be advanced;

(6) Advance a CDC one Classical Circuit Card forward.

At the end of their Turn, the player must discard any extra cards so that they only have a maximum of four cards on hand.

4.4 Building a Quantum Teleportation Circuit

In this section, we describe how a player can obtain a QDC through Aim 1. In short, there are two parts to Aim 1. The player must first build a QTC, and only after they have completed it, they can execute an instance of quantum teleportation. The building blocks of a QTC are the Circuit Cards. Each Circuit Card bears a diagram which represents a circuit element needed to build a QTC.

As explained in Section 3, the protocol for quantum teleportation has two parts: the quantum part consists of a shared entangled state, a measurement, and an error correction; the classical part consists of communication where the transmitting party tells the receiving party about the outcome of the measurement in the quantum part. The design of Circuit Cards tries to reflect this as much as possible.

Quantum Circuit Cards consist of Entang-

ler, Pauli Correction, and Quantum Circuits, whereas Classical Circuit Cards consist of only the Classical Circuits. There exist Swap Circuits, whereas its name implies, swap between the positions of classical and/or quantum "wires". Here, "wire" is used in the same context as in Section 3.

The quantum part of a QTC must begin with an Entangler and end with a Pauli Correction. Quantum or Swap Circuits can be used in between these two cards without any limits, at the player's discretion. Meanwhile, the classical part of a QTC must consist of the same amount of cards as the quantum part.

Figure 14 shows a screenshot of the Beginner setup gameplay, where both players have completed their own QTC. We note that the cards are oriented sideways to reflect the orientation of the cards in a practical game. The QDC and Classical Coin are always on the player's left and the QTC is read from left to right, so the arrows show how to read the QTC from both player's perspective.

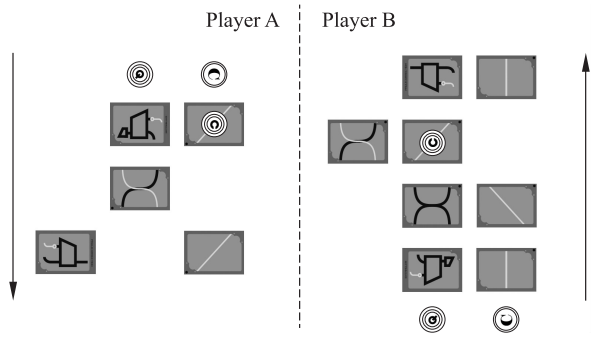


Fig. 14 Beginner setup of Quantum Port. Both players have completed their QTC and are advancing their CDC respectively. Player A requires three Moves to execute an instance of quantum teleportation, while Player B requires two Moves

The quantum part of Player A's QTC is a typical three-card build with Entangler, Swap Circuit, and Pauli Correction. QDC marks the beginning of the quantum part of QTC, hence Entangler is placed on the immediate right of Player A's QDC. The Quantum Circuit on the Swap Circuit goes from top to bottom, so Pauli Correction must be placed below the Swap Circuit. The classical part of Player A's QTC also follows a three-card build that begins from the Classical Coin, and simply needs to be connected by following the orientations of the Classical Circuits.

Meanwhile, Player B's QTC shows a four-card build. Notice that both of the Swap Circuits have a "redundant" wire. It is understood that Player B chooses the necessary Quantum Circuits on both Swap Circuits to complete the quantum part of QTC.

4.5 Executing quantum teleportation

Once a player has completed a QTC, they can execute an instance of quantum teleportation. A CDC is selected by rolling a Four-Sided Die, where the outcome of the die roll is revealed to both players. The player then refers to the Dice Rule in Table 2 and identifies the corresponding CDC based on the outcome of the die roll and the QDC selected at the beginning of the game. The CDC is placed on the first Classical Circuit Card of the player's QTC with head facing down. This whole process is considered as one Move. Afterwards, advancing the CDC one Classical Circuit Card forward will take one Move. An instance of quantum teleportation is completed when the CDC advances beyond the final Classical Circuit Card in the QTC and the player obtains the QDC. As an example, in Fig. 14, both players are attempting to advance their CDC to complete a single instance of quantum teleportation.

Table 2 Dice Rule to decide the corresponding CDC

	00	01	10	11
Ψ^+	1	4	2	3
Ψ^-	2	3	1	4
Φ^+	4	1	3	2
Φ^-	3	2	4	1

Figure 15 shows a screenshot of the Default setup of gameplay with two QDC. Each QDC has

to begin with their respective Entangler, however it is possible to have one Pauli Corrections for two QTC, as shown by Player B's build. On the other hand, Player A in Fig. 15 has three Pauli Correction, where one of the QDC has two choices of Quantum Circuits to execute an instance of quantum teleportation. The Swap Circuit does not play the role of swapping the position of two processes. Instead, it plays the role of branching the Quantum Circuits into 2 possible "paths".

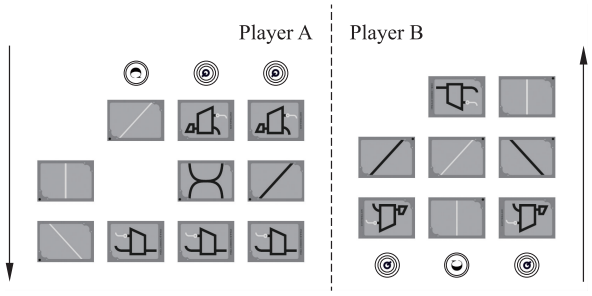


Fig. 15 Default setup of Quantum Port. Both players have completed their QTC

Both scenarios depicted in Fig. 15 are in conflict with CQM's compositional rules of wires and a process. We partially remedy this issue by prohibiting the execution of concurrent quantum teleportation. This means that one must advance a CDC beyond the final Classical Circuit Card in the QTC to complete an instance of quantum teleportation before beginning the next instance of quantum teleportation. While this does not completely resolve the conflict with CQM, we stress that the quantum and classical parts of an instance of quantum teleportation are well-defined at any moment during the gameplay.

4.6 Opponent sabotage

A player can sabotage their opponent by using an Action Card during their Turn. There are four types of Action Cards.

(1) Circuit Destroyer, which destroys one Circuit Card in the opponent's QTC;

(2) Information Jammer, which freezes the opponent's CDC from advancing for one Turn;

(3) Information Revealer, which reveals the opponent's advancing CDC;

(4) Eavesdropper, which steals the opponent's QDC if the player correctly guesses the symbol on the QDC. If the guess is wrong, the player is prohibited from stealing the QDC for the rest of the game.

To obtain a QDC through Aim 2, a player can either use Eavesdropper by itself or Information Revealer followed by Eavesdropper. Ideally, the latter will give the player a sure chance of correctly guessing the QDC, while the former has a 1 in 4 chance of guessing correctly. For the Default setup, Information Revealer only shows the corresponding CDC to one of the two possible QDCs. The player still needs to guess the correct QDC that the opponent is trying to teleport.

Since the whole game is designed to match diagrammatically, it is possible to avoid using jargon when teaching the game. In addition, since most of the physical operations performed in quantum teleportation are embedded into the gaming rules, players learn about quantum teleportation without actively realizing it. A few guiding questions at the end of the gaming session can help to link the two, for example,

(1) What is this game about?

(2) In your opinion, why do you need two circuits, "Q" and "C", to send the data across?

(3) What will happen if you only build one circuit, "C" or "Q", to send the data?

(4) Will you be able to access to the QDC if you only have access to either one of the circuits, "C" or "Q"?

(5) Will you be able to guess the QDC if you do not know about the outcome of the die roll?

5 Conclusion

In this work, we proposed the gamification of categorical quantum mechanics (CQM) on quantum teleportation as a science game for public engagement. Our current prototype model

suffices to demonstrate the quantum teleportation protocol through gaming without utilizing complicated mathematical concepts. The next natural step of improvement that one can aim for is to include the idea of classical and quantum encryption into Quantum Port. It is not necessary to redesign the whole game but merely introducing new cards for the encryption mechanics as an expansion pack.

Supplementary information.

Declarations

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study. All printable materials related to Quantum Port are available through the Supplementary Materials. For a complete set, print one copy of "Game rules. pdf", one copy of "Quantum Port Coins. pdf", two copies of "Quantum Port Cards. pdf", and prepare a four-sided die.

Competing interests

The authors declare that they have no competing interests.

Funding

The prototype of Quantum Port was completely self-funded.

Authors' contributions

PSC and AR gamified the diagrammatic rules of quantum teleportation into Quantum Port. ANA created the artworks for Quantum Port. PSC, AR and NMS contributed in writing and proofreading the manuscript. All authors read and approved the final manuscript.

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Quantum Port was used in two artscience events.

(1) *Not Art, Not Quantum* co-organized by Clarissa Ai Ling Lee, Andrew Jia Cherng Chong, Pak Shen Choong, and Afiqa Nik Aimi on 16 November 2024;

(2) *1st Quantum Valentine Fest* co-organized by Taechasith Kangkhuntod from CreativeLab and The Institute of Fundamental Study, Naresuan University, Thailand on 14 February 2025.

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