Quantum Go: Designing on a Quantum Computer

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Quantum Go: Designing on a Quantum Computer

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The strategic Go game, known for the tedious mathematical complexities, has been used as a theme in many fiction, movies, and books. Here, we introduce the Go game and provide a new version of quantum Go in which the boxes are initially in a superposition of quantum states $|0\rangle$ and $|1\rangle$ and the players have two kinds of moves (classical and quantum) to mark each box. The mark on each box depends on the state to which the qubit collapses after the measurement. All other rules remain the same, except for here, we capture only one stone and not chains. Due to the enormous power and insane speed of quantum computers, compared to classical computers, we may think of quantum computing as the future. So, here we provide a tangible introduction to superposition, collapse, and entanglement via our version of quantum Go. Finally, we compare the classical complexity with the quantum complexity involved in playing the Go game.

I. INTRODUCTION

The door of quantum computing was opened by the works of Benioff[3], Manin[2], and Feynman[4], and the concept was raised by Jozsa[5] and others. Processing power and memory optimisation are the key advantages of quantum computers, the impetus being entanglement and superposition[31]. A limitation is quantum decoherence[8,9], caused by the interference of qubits with the surroundings. Still, quantum computers are thought to solve several complex problems and simulate quantum physics far better than classical counterparts.

Quantum game theory was developed[6] from the works of Wiesner on quantum money[10], followed by the works of Deutsch and Jozsa[5] on quantum information and game theory formalism by Meyer[12] and Eisert[7]. Lately, it has attracted much attention, be it quantum Tic-Tac-Toe (by Sagole *et al.*)[11], quantum Sudoku (by Pal *et al.*)[13], quantum Go (by Ranchin)[14], quantum Chess (by Kartavicius)[15], quantum Pong (by Verma *et al.*)[16], quantum Bingo (by Singh *et al.*)[17], quantum Monty Hall (by Paul *et al.*)[18] or quantum Diner's Dilemma game (by Anand *et al.*)[19] to name a few.

In today's era of artificial intelligence, deep learning methods and artificial neural networks have made tremendous developments. We can remark the example of the dominance of computer programs over human players in Go game: DeepMind technologies developed AlphaGo[20], which became the first Go program to beat a professional Go player on 19 × 19 board[29]. Its playing style is having more probability of victory by fewer points rather than less winning probability by more points[30]. It was succeeded by three more powerful programs, namely AlphaGo Master, AlphaGo Zero, and AlphaZero. To make it more challenging for the computers to master, we have provided a novel variant of the quantum Go game and simultaneously tried to provide the reader an interesting exposure to some basic quantum phenomena such as superposition, collapse, and entanglement.

IBM quantum experience (IBM QE)[1], a superconducting quantum computing system provides user-friendly access to the quantum computers to the researchers all around the globe. Many important applications have been found by IBM QE[21–28]. In this paper, a 16-qubit quantum simulator and a 5-qubit quantum computer are used to create superposed states in the 4 × 4 quantum Go board. Also, we have shown the circuits used during the first two moves in the game.

II. CLASSICAL GO GAME

Like Chess, Go game is a deterministic perfect information game where no information is hidden from either player, and there are no built-in elements of chance, such as dice. It is a two-player game, in which the aim is to surround more territories than the opponent.

Go, probably the world's oldest board game[32] is thought to have originated in China some 4000 years ago. According to some sources, this date is as early as 2356 BCE. The game was probably taken to Japan about 500 CE, and it became popular during the Heian period (794-1185). The modern game began to emerge in Japan with the subsequent rise of the Samurai class. It was given special status there during the Tokugawa period (1603-1867) when four highly competitive Go schools were set up and supported by the government and Go-playing was thus established as a profession. The game became highly popular in Japan in the first half of the 20th century; it was also played in China and Korea, and its following grew there in the latter decades of the century. Play spread worldwide after World War II[32]. As recently as 20 years ago, formal games between Go masters from different countries were practically unheard of. The last 10 years have seen a historic proliferation of international championships, where the great players from Japan, China, Korea, and elsewhere compete to be seen as the world's best player. Annual events include the Fujitsu cup and the Dongyang securities cup. More recently, it is being played electronically[32].

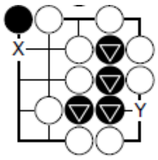

FIG. 1: The black stone is captured if white puts in 'X' and all the black stones marked with triangles get captured if white puts in 'Y'

A. Rules of Go

1. **Basics:** The 13 ×13, 9×9, or 19×19 board starts empty. One player has black stones and the other has white. Black goes first, and then the players take turns in which a stone is to be put down on the board on the corners of the squares.
2. **The object of the game:** At the end of the game we score one point for each point of territory we have, and one point for each stone we have captured. The person with the most points wins.
3. **Territory:** If on moving from a white (or black) point along the lines of the board, we always come to the edge of the board or a white (or black) stone, never a black (or white) one. Then these empty points belong to white (or black).
4. **Liberties:** The liberties of stone are the empty points that are next to it. A stone at the corner has 2 liberties, at the edge has 3 and others have 4. Liberties are important because if a stone runs out of them it will be captured!
5. **Chains:** If we put two of your stones next to each other, they become a small chain.
6. **Capturing:** The isolated black stone in the 1 has only one liberty left, marked with an X. If we are White, then we can capture this stone. We play at X and take away the last liberty. We can then take this black stone off the board. Capturing a chain of stones works in the same way as for a single stone. The chain of four black stones marked with triangles has just one liberty, marked Y. If we are White and play there then we take off the whole black chain!
7. **Suicide:** If we place a stone to form a chain without any liberty, it is a suicide in the game.
8. **When does the game end?** When it is our turn, instead of making a move we can pass. Whenever we pass give an extra stone to the other player to add to their captures. The players usually pass when there is no further chance to surround more territory or attack enemy stones. When both players pass, one after the other, the game is over. To make the number of the moves the same for both players, white must pass last, even if this means the third pass in a row[33].

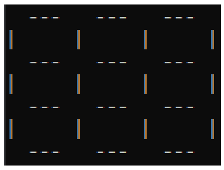

FIG. 2: 4 ×4 quantum Go game board before the game starts.

Hence, the general strategy should be clear:

- Try forming chains,
- Try gaining territories,
- Protect stones,
- Avoid suicides.

III. QUANTUM GO GAME

This section gives a detailed description of our version of the quantum Go game. The game uses simple quantum computing principles, which makes it different and more interesting than the regular classical version of Go. The basic rules are almost the same with a major difference being the inclusion of probability in the classical game. In the game, a player chooses a particular box in his (or her) turn and the output is either Black or White with a 0.5 probability each. Another modification in our game is that only the capture of a single stone will be considered, and for simplicity, the capture of chains will be ignored. Let us look for our game version in a simple 4×4 board. Initially, the board is set up as 2.

and each box is in a superposition of states $|0\rangle$ and $|1\rangle$. It is a quantum state that has an equal probability of collapsing into a classical state, i.e $|0\rangle$ or $|1\rangle$. The game allows two legal moves:

1. **Classical Move:** When applied to a box, it collapses to either of the classical states with equal probabilities.
2. **Quantum Move:** It requires a control box and a target box. It uses the concept of *quantum entanglement* by entangling the target box with the control box in such a way that when a classical move is applied to the control box, both collapse to the same state.

A *classical move* cannot be applied to the same box twice. Quantum move's target box should be in a classical state, and the control box should be in a quantum state so that when the quantum state of the control box collapses to the favored state of the player, it reverses the classical state of the target box. Black player's favored state is $|1\rangle$, and player white player's favored state is $|0\rangle$. A box is marked 'B' when it collapses to state $|1\rangle$ and 'W' when it collapses to state $|0\rangle$.

Let us look at an example of how the game works. Our two players are Bob (Black) and Alice (White).

Bob takes the first turn which ought to be classical move as there is no box in the classical state for being the target for his quantum move. So, he chooses any one of the 16 boxes, and the chosen box collapses into either state $|0\rangle$ or $|1\rangle$. Suppose, he is lucky and the box collapses to $|1\rangle$ state, which is shown by marking the box 'B'. Now, Alice's turn: she may choose to go for a classical move and collapse any of the other boxes or may play a quantum move and entangle another box with the box marked 'B', the latter being the target of the entanglement. Now, whenever a classical move is applied onto the control box and if it collapses to classical state $|0\rangle$, it automatically reverses the state of the target, which in this case makes the previously 'B' marked box 'W'. But if the control collapses into $|1\rangle$ state, then the target state would remain the same. The board and the number of stones captured after each step will be shown and after the game is over, the players can count their territory numbers by Rule-3 and the winner will be decided by Rule-8.

IV. CIRCUIT EXPLANATION

The quantum circuit is set up with 16 qubits, and 16 classical bits and Hadamard gates are applied to each qubit. Hadamard gate creates the superposition state, which we call the quantum state. Let us say Bob chooses to go for a classical move on box 4, then as soon as the input is received the qubit associated with box 4 (i.e. qubit 3 as qubits count start from qubit 0) is measured and the result is analyzed. Box 4 is marked 'B' if the result is $|1\rangle$ and 'W' if the result is $|0\rangle$. To ensure, qubit 4 does not alter in subsequent moves, we add a Reset gate if it collapses to $|0\rangle$; or a Reset followed by a Not gate if it collapses to $|1\rangle$. Now it is Alice's turn and let us say she chooses to go for a quantum move. So, she entangles box 4 with let us say box 2 (i.e., qubit 3 with qubit 1), with box 4 being the target and 2 being the control. An anti-control NOT gate is applied, with qubit 1 being the control and qubit 3 the target. What this move does is, if qubit 1 is measured and it collapses to $|0\rangle$, then the anti-control NOT gate would reverse the state of qubit 3 and the previously marked 'B' would change to 'W', which would ultimately make both box 2 and box 4 marked as 'W'. On the contrary, if qubit 1 collapses to $|1\rangle$, anti-control NOT gate would not be able to reverse the state of qubit 4, and both boxes would be marked 'B'. The game continues similarly until both players agree to pass. An anti-control NOT gate is added if the white player goes for a quantum move and a control NOT gate is applied if the black player goes for a quantum move. The required circuits for the above explanation are shown on the next page.

V. BUILDING THE GAME[34]

A. STEP-1

Making the board: board()

- Takes the input from the user for board size and print board of that size (as shown above for 4×4).

B. STEP-2

Generating the circuit: setup()

- Generates a circuit of n^2 qubits and n^2 classical bits, n^2 being the board size.
- Adds Hadamard gate to all the qubits.
- Prints the rules of the game.

C. STEP-3

Notifying whose turn: turn()

- Checks whose turn it is and prints accordingly.
- Asks the player for classical or quantum move and corresponding position and calls cmove() or qmove() accordingly.
- Else if the player chooses to pass, looks for the response of the other player and if all agree, ends the game, ensuring white passes last.

D. STEP-4

Classical move: cmove()

- Calls the Aer() function from the qiskit library
- Simulates the circuit on qasm simulator
- Checks if the position is already marked
- Checks if the position is entangled with any other position due to previous moves
- If yes, adds CNOT or anti-CNOT as mentioned before
- Else collapses the qubit by measuring that position and fixes its state
- Calls the mark() function

E. STEP-5

Quantum move: qmove()

- Stores the inputs in control and target lists
- Prints 'The control and target positions have been entangled'

F. STEP-6

Removing the trapped stones: remove()

- Checks all the stones after each step and removes the particular stone that has no liberty.

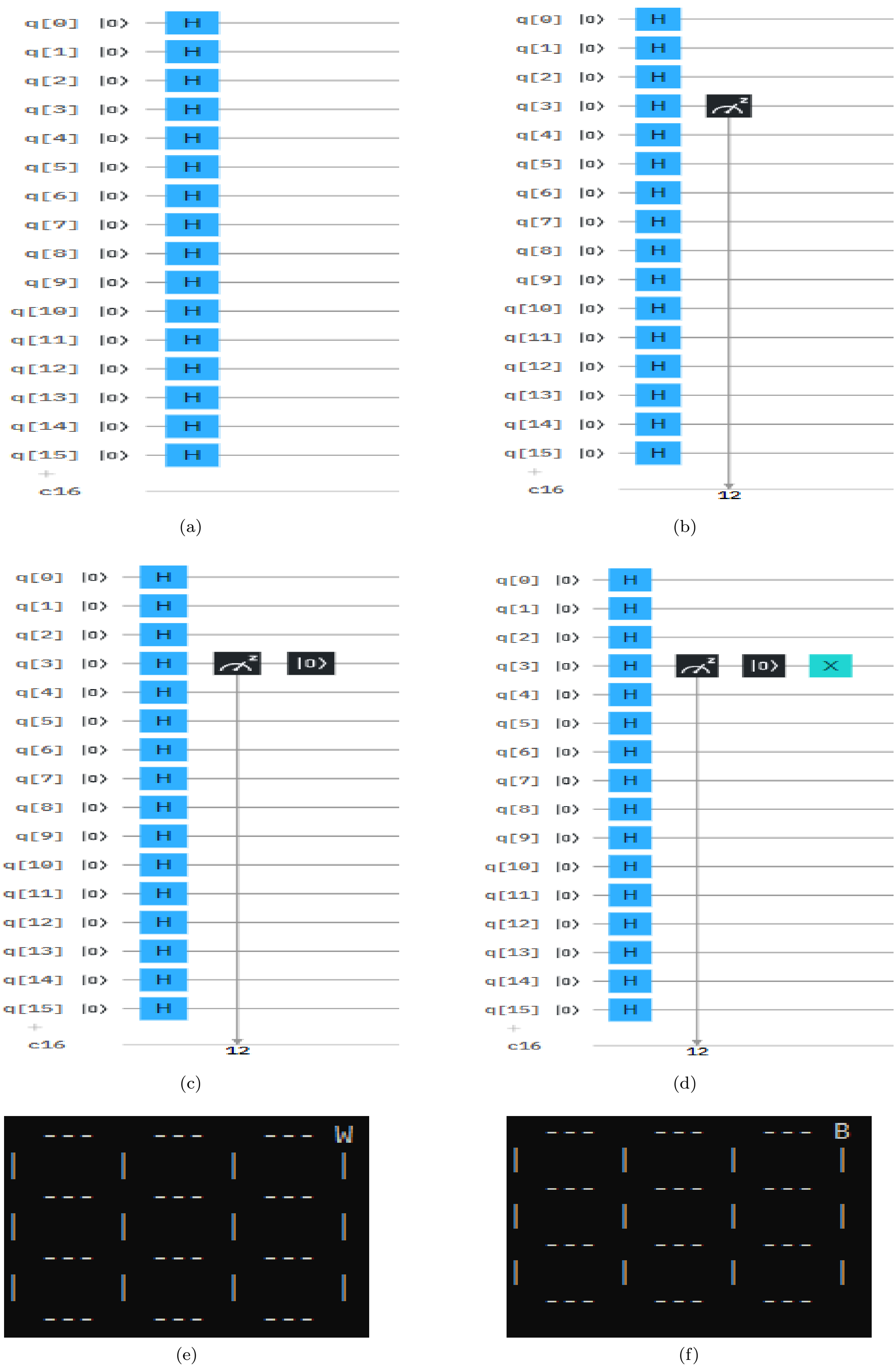

FIG. 3: Circuit explanation and output after first move: (a) the basic circuit with 16 qubits and 16 classical bits for 4×4 board; (b) measuring the first chosen box (here 4 i.e. q3); (c) adding Reset gate if the measured value is $|0\rangle$; (d) adding a Reset and a Not gate if the measured value is $|1\rangle$; (e) Output if measured value is $|0\rangle$; and, (f) Output if measured value is $|0\rangle$

G. STEP-7

Printing board after each step: mark()

- Re-simulates the circuit
- Prints the board as per moves made in respective turns by the players by calling the remove() and board() functions.
- Returns the number of white and black stones captured

This is how cmove and qmove work in our game. This will be iterated in the subsequent moves in the game.

VI. QUANTUM METAPHORS

Quantum Go game adds a level of complexity by allowing players to explore the possibilities coming from each position being $|0\rangle$ and $|1\rangle$ at once. This phenomenon simulates quantum superposition, which is the principle that states physical objects need not have a definite attribute. In quantum theory, physical systems exhibiting superposition are studied through a quantum measurement. This can be interpreted as a phenomenon of quantum collapse, where the physical states of a system in superposition are reduced to states which are no longer in a superposition. In quantum Go game, an analogous process occurs when a classical move is applied on a qubit in superposition. Another quantum phenomenon addressed to is entanglement: when the quantum move is applied on the two qubits (control and target), the quantum state of each qubit cannot be described independently until collapse has occurred through the classical move. And after one qubit is measured, the state of the other does not require measurement; knowing one qubit's state defines the other. We can illustrate these ideas concerning the previous example more precisely.

- **Superposition:** In the beginning, all the qubits are in a superposition of $|0\rangle$ and $|1\rangle$ with a 50% probability each.
- **Collapse:** In the first step, 3rd qubit is measured and its state is now well-defined.
- **Entanglement:** In the next step, first and third qubits are entangled by the quantum move. In the later step, on applying anti-control Not gate, the states of both qubits were found to be the same.

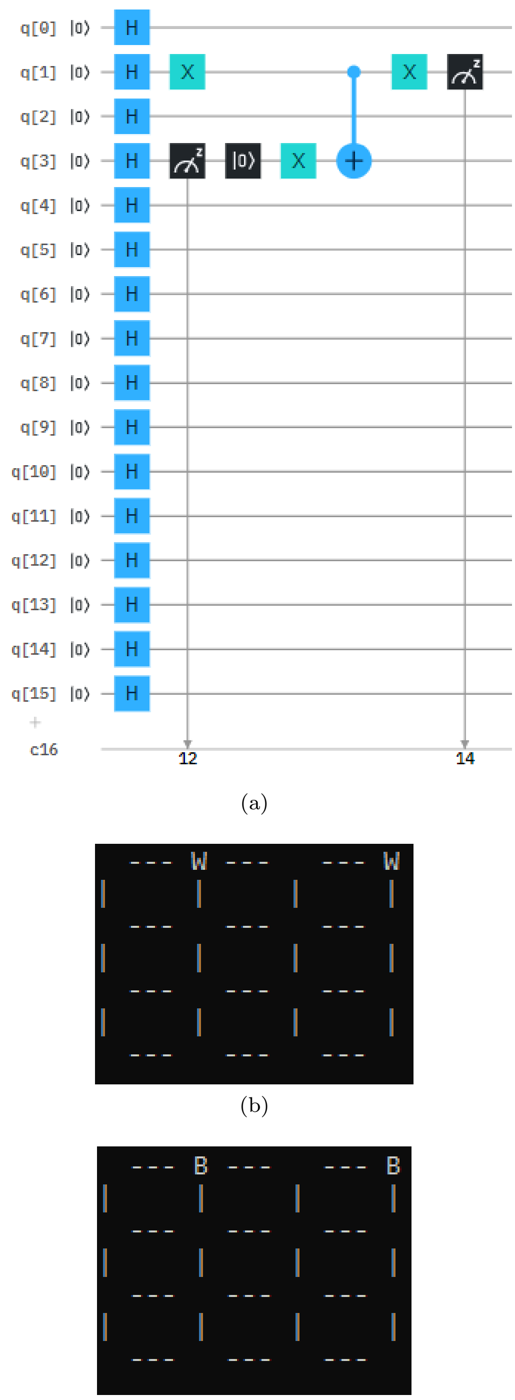

FIG. 4: Circuit explanation and output after first move: (a) this circuit if q3 collapses to $|1\rangle$ and anti-CNOT gate is applied when White chooses quantum move to entangle it with first qubit i.e. second box, (b) this is the output if q1 collapses to $|0\rangle$; q3 changes its state, and (c) this is the output if q1 collapses to $|1\rangle$; q3 remains $|1\rangle$

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Though some of the interesting quantum phenomena such as complementarity, non-locality, and contextuality[35] have no analogs in quantum Go, it is a fun way to get an insight into a few fundamental quantum phenomena.

VII. OTHER VERSIONS

We can devise some variations of the quantum Go game described above. A quantum diagonal Go game may be devised in which only the diagonals will be initially in a superposition of $|0\rangle$ and $|1\rangle$, whereas the other positions will be as in a classical board. A symmetric quantum Go game can be thought of, in which if the board is of even size, the upper half will be initially in superposition, whereas the lower half will be as in classical board or if the board is of an odd size, the center position will be quantum and the one of each point-symmetric pair (about the center) will be in superposition and the other a classical box. These modifications tend to simplify the game, making it easier to play.

VIII. DISCUSSION

Due to the introduction of the probabilistic approach in designing of the game, the naive first impression might be that the game is completely based on luck. However, it is not fully right. Firstly, we all know that probability is inherent in the quantum phenomena. So, in the quantum Go game, the concept of probability is inevitable. Secondly, as the players start playing the game, they will come to realize that we need a proper strategy to follow to be the winner. You need to be strategic during quantum moves while you entangle two boxes. The luck factor is handy only in the case of classical moves. We can note that a good strategy would be not to entangle a box with another which is already in your favored state. Let us illustrate it in the following example: Bob goes for a classical move to collapse any of the boxes, and it collapses to $|0\rangle$. So the box turns 'W' now and if in the next move, Alice entangles this, and the control of this move in any subsequent step collapses to $|0\rangle$ which makes the previously 'W' marked box 'B'.

Strategies should be made before classical moves also. The players need to foresee what effect collapsing of a particular box to either of the states may have on his position in the game. Comparing with the classical Go, this element of probability in quantum Go adds a more exciting feature to the game. It requires more detailed thinking. Depending on the board size, the number of qubits needed is n^2 and accordingly, needed are n^2 classical bits to measure them. For each step, the time complexity is proportional to the number of gates involved. For the same board size, its classical counterpart has $O(n^2)$ time complexity.

IX. CONCLUSION

Here, we have put forward a quite accessible description of some major quantum phenomena, designing an exciting quantum Go game. To conclude, we have described the formulation and working of our version of quantum Go. We have given a brief introduction to classical Go, followed by modified rules in our version of the game, quantum circuit needed for it, and a description of our program for the game, game play in action, insight to some quantum metaphors. At last, we provided two simpler versions of the game that can be thought of and gave a brief discussion on the differences between classical and quantum Go games. To the end, we have provided a simple yet promising version of the Go game using hybrid (quantum and classical) computing. This probabilistic nature of the classically definitive game has made it yet more exhilarating.

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[1] IBM Quantum Experience, https://www.research.ibm.com/ibm-q/
[2] Y. Manin, Computable and Uncomputable (in Russian), Sovetskoye Radio, Moscow (1980).
[3] P. Benioff, The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines, J. Stat. Phys. **22**(5), 563-591 (1979).
[4] R. Feynman, Simulating Physics with Computers, Int. J. Theor. Phys. **21**, 467-488 (1982).
[5] D. Deutsch and R. Jozsa, Rapid solutions of problems by quantum computation, Proc. R. Soc. Lond. A **439** 553-558 (1992).
[6] J. D. Hidary, A Brief History of Quantum Computing, https://link.springer.com/chapter/10.1007%2F978-3-030-23922-0_2
[7] J. Eisert, and M. Wilkens, Quantum Games, J. Mod. Opt. **47**, 2543 (2000).
[8] D. Franklin, and F. T. Chong, Challenges in Reliable Quantum Computing, In: Shukla S.K., Bahar R.I. (eds) Nano, Quantum and Molecular Computing, Springer, Boston, MA (2004).
[9] N. Mishra, B. K. Behera, and P. K. Panigrahi, Decoherence free subspaces for quantum communication in amplitude damping channels, DOI: 10.13140/RG.2.2.26687.05282
[10] S. Wiesner, Conjugate Coding, SIGACT News **15**, 78-88 (1983).
[11] S. Sagole, A. Dey, B. K. Behera, and P. K. Panigrahi, Quantum Tic-Tac-Toe: A Hybrid of Quantum and Classical Computing, DOI: 10.13140/RG.2.2.18883.76320 (2019).
[12] D. A. Meyer, Quantum strategies, Phys. Rev. Lett. **82**, 1052-1055 (1999).

[13] A. Pal, S. Chandra, V. Mongia, B. K. Behera, and P. K. Panigrahi, Solving Sudoku game using a hybrid classical-quantum algorithm, EPL **128**, 40007 (2019).
[14] A. Ranchin, Quantum Go, arxiv:1603.04751 (2016).
[15] Quantum Chess, research.cs.queensu/QuantumChess
[16] C. Varma, B. K. Behera, and P. K. Panigrahi, Playing Pong Game on a Quantum Computer, DOI: 10.13140/RG.2.2.23258.08648/1 (2019).
[17] Vishwanath Singh, Bikash K. Behera, and Prasanta K. Panigrahi, Design of Quantum Circuits to Play Bingo Game in a Quantum Computer, DOI: 10.13140/RG.2.2.22727.34720 (2019).
[18] S. Paul, B. K. Behera, and P. K. Panigrahi, Playing Quantum Monty Hall Game in a Quantum Computer, DOI: 10.13140/RG.2.2.22315.49442 (2019).
[19] A. Anand, B. K. Behera, and P. K. Panigrahi, Solving Diner's Dilemma Game, Circuit Implementation and Verification on the IBM Quantum Simulator, DOI: 10.13140/RG.2.2.28940.05765 (2019).
[20] AlphaGo — DeepMind, https://deepmind.com/research/case-studies/alphago-the-story-so-far
[21] B.K. Behera, A. Banerjee, and P.K. Panigrahi, Experimental realization of quantum cheque using a five-qubit quantum computer, Quantum Inf. Process. **16**, 312 (2017).
[22] D. Ghosh, P. Agarwal, P. Pandey, B.K. Behera, and P.K. Panigrahi, Automated Error Correction in IBM Quantum Computer and Explicit Generalization, Quantum Inf. Process. **17**, 153 (2018).
[23] S. Gangopadhyay, Manabputra, B.K. Behera, and P.K. Panigrahi, Generalization and demonstration of an entanglement based Deutsch-Jozsa like algorithm using a 5-qubit quantum computer, Quantum Inf. Process. **17**, 160 (2018).
[24] P.K. Vishnu, D. Joy, B.K. Behera, and P.K. Panigrahi, Experimental demonstration of non-local controlled-unitary quantum gates using a five-qubit quantum computer, Quantum Inf. Process. **17**, 274 (2018).
[25] S. Satyajit, K. Srinivasan, B.K. Behera, and P.K. Panigrahi, Nondestructive discrimination of a new family of highly entangled states in IBM quantum computer, Quantum Inf. Process. **17**, 212 (2018).
[26] B.K. Behera, S. Seth, A. Das, and P.K. Panigrahi, Demonstration of entanglement purification and swapping protocol to design quantum repeater in IBM quantum computer, Quantum Inf. Process. **18**, 108 (2019).
[27] M. Kapil, B. K Behera, and P. K. Panigrahi, Quantum simulation of Klein Gordon equation and observation of Klein paradox in IBM quantum computer, arXiv:1807.00521 (2018)
[28] M. Swain, A. Rai, B. K. Behera, and P. K. Panigrahi, Experimental demonstration of the violations of Mermin's and Svetlichny's inequalities for W and GHZ states, Quantum Inf. Process. **18**, 218 (2019).
[29] Google AI Blog, https://ai.googleblog.com/2016/01/alphago-mastering-ancient-game-of-go.html (2016).
[30] AlphaGo's unusual moves prove its AI prowess, experts say, https://www.pcworld.com/article/3043668/alphagos-unusual-moves-prove-its-ai-prowess-experts-say.html
[31] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, Quantum entanglement, Rev. Mod. Phys. **81**, 865 (2009).
[32] Go Game, https://www.britannica.com/topic/go-game
[33] Go Rules, https://www.britgo.org/files/rules/GoQuickRef.pdf
[34] To play our Quantum Go game, copy the code from here, and run the code in jupyter notebook, google colab or any other similar software: Quantum Go Game
[35] S. Roy, B. K. Behera, and P. K. Panigrahi, Experimental realization of quantum violation of entropic noncontextual inequality in four dimension using IBM quantum computer, arXiv:1710.10717 (2017).