Abstract Quantum Systems and the Possibilities for Paradox-Free Backwards-in-Time Causality

Allan Goff[*], Dale Lehmann[†] and Joel Siegel[‡]
Novatia Labs, Folsom, CA, 95630, AllanGoff@NovatiaLabs.com

In previous work, the authors have shown that spacelike causal connections can be made relativistically consistent within the quantum formalism by the introduction of symmetric spacetime intervals. Since spacelike causal connections permit both Faster-Than-Light (FTL) signaling and Backwards-in-Time Causality (BTC), the specter of temporal paradox must be dealt with. Closed timelike loops in spacetime can be either paradoxical or indeterminate, so a censor mechanism must prevent the construction of all closed timelike loops, or at least the paradoxical ones. In the latter case, a new problem emerges: causeless information can occur in indeterminate closed timelike loops. This paper introduces Abstract Quantum Systems (AQS) as a way to study systems involving these phenomena. The most thoroughly studied AQS is Quantum Tic-Tac-Toe. An AQS can be constructed from any classical system by adding three types of rules: Rules of Superposition, Rules of Entanglement, and Rules of Collapse. Such quantum systems can be placed into a one-to-one correspondence with a simultaneous set of classical systems called the classical ensemble. While superficially similar to the Many Worlds interpretation of quantum mechanics, the classical ensemble idea is significantly different. This paper shows that the classical ensemble supports a censor mechanism that prevents BTC from generating temporal paradoxes while allowing indeterminate closed timelike loops. This censor mechanism works by pruning from the classical ensemble any classical reality that has become contradictory due to superposition and entanglement. In other words, temporal paradox does what it was always feared it would do; it breaks the universe. However, it only breaks classical ones. As long as it does not break all the classical realities in the ensemble, the quantum reality persists. When a collapse occurs, one of the classical realities remaining in the ensemble is randomly chosen. In this way, the persisting realities left in the classical ensemble represent the weighted indeterminacy of states. Therefore, in addition to avoiding temporal paradox, the classical ensemble also explains the causeless appearance of information in indeterminate closed timelike loops. The information is simply "concentrated" from realities that "no longer exist." This is formally similar to quantum computing, but now in spacetime, rather than just in space. The conclusion is that physical quantum systems may support both FTL and BTC without paradox, implying the possibility of a technology that amounts to a limited analog of time travel.

Nomenclature

$|1\rangle$ = Basis state in Quantum Tic-Tac-Toe, a square on the board
Ψ = Quantum state, typically a superposition of basis states

I. Introduction

THIS paper is the fifth of eight integrated papers[1,2,3,4,5,6,7,8] to explore the potential of quantum nonlocality to support superluminal signaling; i.e., communicating at faster-than-light (FTL) speeds[9]. Spacelike causality raises a number of issues that must be addressed if nature is to permit any kind of FTL phenomenon. These include consistency with Special Relativity, a broadened formulation of causality, and either resolution or avoidance of temporal paradox[10]. These issues are addressed with increasing sophistication through the series of eight papers.

* President, Novatia Labs, 9580 Oak Ave. Parkway, #7-110, AIAA Member.
† Software Engineer, Novatia Labs, 9580 Oak Ave. Parkway, #7-110, AIAA Member.
‡ Professor, Sierra Community College, Rocklin, CA, AIAA Member.

This paper introduces abstract quantum systems (AQS), with particular emphasis on Quantum Tic-Tac-Toe[11]. The general procedure for constructing an AQS from a classical system is presented, and then implemented for Classical Tic-Tac-Toe. Examples of the rules, features, and resulting metaphors are briefly covered. A central feature of AQS is the prevalence of self-collapse through cyclic entanglements; a formal measurement process without the need for an "observer" outside the quantum systems. Such self-collapses inevitably involve backwards-in-time causality (BTC). A prototypical example of BTC is shown for Quantum Tic-Tac-Toe demonstrating how the future can influence the past in a paradox-free manner. The paper finishes with a look at the implications for quantum physics and concludes that a limited form of time travel cannot be ruled out.

I. Background

Why consider a limited and admittedly arbitrary quantum system when reality provides such a rich one? There are three reasons. First, a guiding principle of science is the principle of reductionism; we come to understand the whole by first understanding the parts. Quantum mechanics is a complicated whole. Teasing it apart is inherently a promising approach. Second, a guiding principle of lateral thinking is to change the problem[12]. Considering contrafactuals within the same problem space is a proven technique for thinking out of the box. Third, quantum mechanics is apparently up against a paradigm barrier (we need to think out of the box)[13]. The measurement problem, foundational to quantum mechanics, remains unsolved to this day and some think is high time we developed an objective measurement mechanism[14]. Quantum mechanics stands alone amongst modern theories in that it suffers from a plethora of "interpretations"[15].

The previous paper explored the hypothesis that self-referential entanglements along symmetric spacetime intervals might provide a measurement process for quantum systems. While self-reference is fundamental to nonlinear processes, logical self-reference remains poorly understood, but examples abound, sometimes in the strangest places[16]. Since quantum systems exhibit nonlocality, they may yet support faster-than-light (FTL) phenomenology, and since FTL is tantamount to time travel, the issue of temporal paradox is not far from quantum physics. Our developing thesis is that quantum temporal paradox (QTP) is the measurement mechanism.

I. Conceptual Development

We are going to define Abstract Quantum Systems as the addition of three types of rules to any classical system. These rules are…

1. Rules of Superposition
1. Rules of Entanglement
1. Rules of Collapse

The best studied AQS is Quantum Tic-Tac-Toe, which has been developed in some detail. The underlying classical system is Tic-Tac-Toe, a well-known child's game. Players take turns, making marks (either an X or an O with player X going first), into a 3x3 grid of squares. First player to get three marks in a row wins. Only one mark is permitted per square. For Quantum Tic-Tac-Toe there is just one rule of each type. In the case of Quantum Tic-Tac-Toe the rule of entanglement and the rule of collapse can be derived from the rule of superposition, a feature we found suggestive given Feynman's flamboyant claim that superposition contains the entire mystery of quantum mechanics[17].

A. The Rule of Superposition

The *Rule of Superposition* is that on every move, a player must mark two squares; his move is half in one square and half in the other. It is not in both, but it is potentially in either. It is in a *super*position. These two marks are called spooky marks (taken from Einstein's quip about the spooky action at a distance implied by quantum nonlocality) and will be identified as a pair by the move number. Therefore, all of X's spooky marks are identified by odd numbers, and O's by even numbers.

The natural interpretation of superposition is that the state of the quantum game implies a set of simultaneous classical games called the classical ensemble. Figure 1 shows the state of the quantum game and the classical ensemble for a potential game where two moves have transpired. On the left is the status of the quantum game after two moves, on the right is the classical ensemble. X's first move is half in square 1 and half in square 2. When X made his first move, it split "reality" in two. In half the classical games in the classical ensemble, X is in square 1 and in the other half he is in square 2. Similarly, O's first move (move 2 of the game) is half in square 5 and half in square 8, and her move split each of those realities in two, yielding a total of four games in the classical ensemble. Therefore, in half the realities in the classical ensemble, O is in square 5 and in the other half she is in square 8.

We can represent the state of the game by adopting a notation from quantum mechanics: basis vectors and their superpositions. In the classical game, the property of a move is which square it is in, so the squares make a natural basis. Every classical move can be in any of nine states (squares), which we will simply label one through nine;

$$|1\rangle \quad |2\rangle \quad |3\rangle \quad |4\rangle \quad |5\rangle \quad |6\rangle \quad |7\rangle \quad |8\rangle \quad |9\rangle \tag{1}$$

A quantum move represents a state that is a superposition of basis states. A superposition looks like this;

$$\Psi_1 = |1\rangle + |2\rangle \tag{2}$$

which captures X's first move. Note that the rules of Quantum Tic-Tac-Toe only allow superpositions in two squares. Clearly greater superpositions could be allowed in a variation or in other AQS. Note also that these are unweighted superpositions; quantum mechanics generally uses complex superpositions. One more difference is that squares form our only measurement basis, so there are also no conjugate variables. By eliminating these extra complexities, Quantum Tic-Tac-Toe highlights certain features of quantum mechanics and suppresses others.

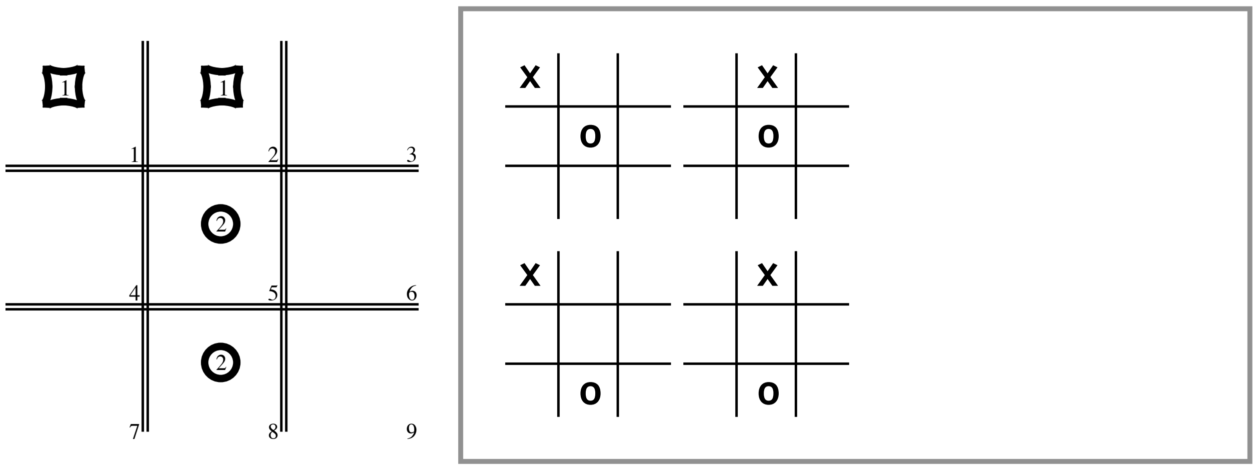

Figure 1: Superposition

O's move is also in a superposition;

$$\Psi_2 = |5\rangle + |8\rangle \tag{3}$$

so the state of the system is a product state of the two moves;

$$\begin{aligned} \Psi_{12} &= \Psi_1 \Psi_2 \\ \Psi_{12} &= |1\rangle_1 |5\rangle_2 + |1\rangle_1 |8\rangle_2 + |2\rangle_1 |5\rangle_2 + |2\rangle_1 |8\rangle_2 \end{aligned} \tag{4}$$

Such states are said to be separable. For initial clarity, the move each state stands for has been subscripted with the number of the move. This gets unwieldy quickly; therefore, our standard will be that the states are always in move order, so that we can suppress the subscripts without confusion.

A. The Rule of Entanglement

The *Rule of Entanglement* can be seen by considering a different move for O, say squares 2 & 5. This is shown in Figure 2. Since O has also laid claim to a square that X has a spooky mark in, when the two realities from the first move of the game are split into four realities one of them is in a contradictory state. In Classical Tic-Tac-Toe two marks cannot be in the same square, we therefore throw such realities out. Contradictory classical realities are pruned from the classical ensemble and will be suppressed from now on. Pruning via contradiction leads to non-separable states and therefore an entanglement of the moves that generated the contradiction.

This is the defining difference between the classical ensemble and the Many Worlds Interpretation. In Many Worlds, the realities split when a measurement is made and become independent universes. In the classical ensemble, realities are split upon superpositions and pruned by entanglements. As we will see below, measurements are triggered by cyclic entanglements and lead to the removal of additional realties from the ensemble by invoking a second kind of move. Unlike Many Worlds, realities in the classical ensemble are not separate but form an integrated whole.

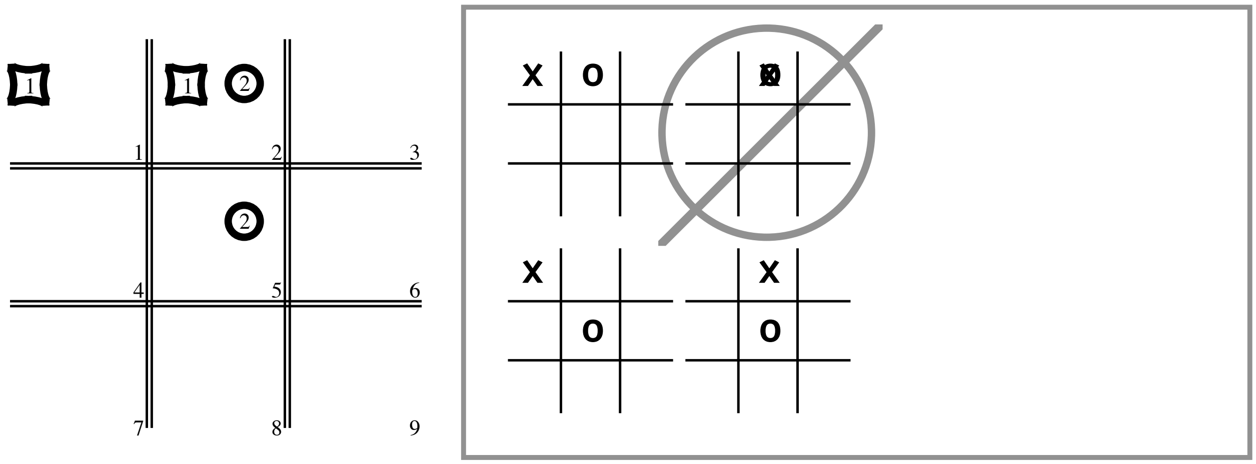

Figure 2: Entanglement

It is worth checking out the state equation for this situation. First, look at the superposition states of the two moves;

$$\Psi_1 = |1\rangle + |2\rangle$$
$$\Psi_2 = |2\rangle + |5\rangle \tag{5}$$

but they are no longer separable;

$$\Psi_{12} \neq \Psi_1 \Psi_2$$
$$\Psi_{12} = |1\rangle|2\rangle + |1\rangle|5\rangle + |2\rangle|5\rangle \tag{6}$$

and because they are not separable, they are entangled. When X makes his next move, he will split the three realities in the classical ensemble in two for a total of six. If this move does not create an entanglement, all six will be legal and persist. On a simple entanglement, two of the classical realities will be contradictory, and so only four realities will persist. However, if X moves such as to make a cyclic entanglement, then a measurement event is triggered and we need a collapse rule.

A. The Rule of Collapse

The *Rule of Collapse* is invoked whenever a cyclic entanglement occurs. An entanglement is cyclic if there exists a path from one spooky mark back to itself. In general, a cyclic entanglement leaves only two realities in the classical ensemble; all the others will be contradictory. To avoid the possibility of an entanglement that could make all the realities in the ensemble contradictory, a collapse to pure classical states must now occur. In this case, one of the players must choose which way the cyclic entanglement collapses, i.e., they must choose which of the two realities in the ensemble will continue and which one will be eliminated even though neither is contradictory. Figure 3 shows one move that X might make that creates a cyclic entanglement. To see the self-referential path of the cyclic entanglement, note that move one depends on move two, which depends on move three, which depends on move one; therefore move one depends on itself. There is a resulting ambiguity in causality, which is resolved by having one of the players make a new kind of move, a choice move, which specifies which way collapse happens.

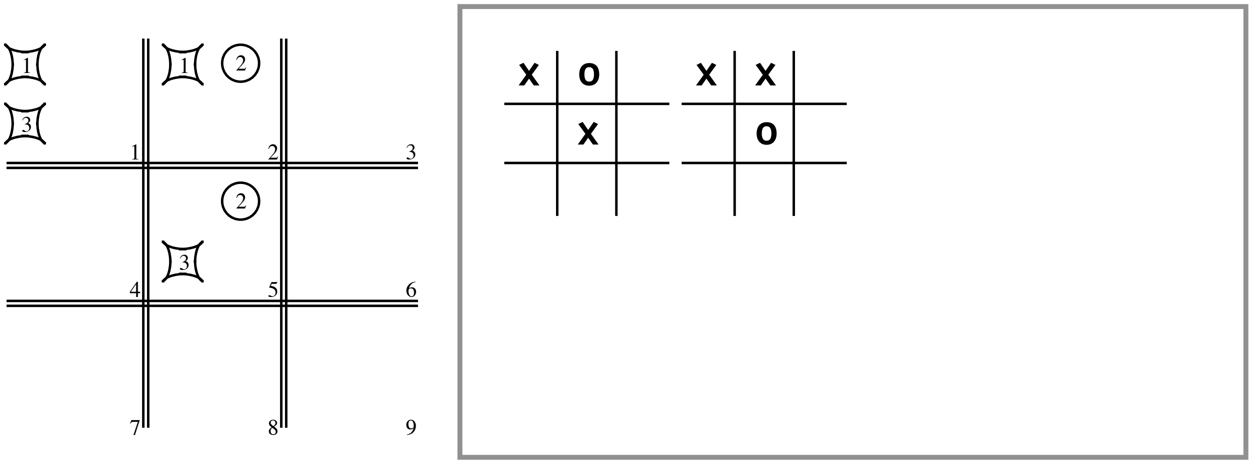

Figure 3: Cyclic Entanglement

We have ghosted the spooky marks a little to indicate that they are in a cyclic entanglement. To balance the game strategically, we specify that if one player creates the cyclic entanglement, the other player gets to choose the collapse. Therefore, O gets to choose which of the two realities in the classical ensemble persists and which gets pruned. She might reason that she will end up either in the side or in the center, and since the center is the more powerful square she will choose the second of the two realities. If she makes this choice, then the superposition of her first move collapses to the center square, which means X's second move cannot be there, so it must be in the corner, which forces his first move into the side square, which forces her move into the center square as she chose. A similar causality chain exists if she chooses the side square. By making her choice, she has collapsed the state of the moves on the board to pure classical positions. The collapse induced by cyclic entanglement has resulted in a measurement event – and no reference to an "observer" was necessary. Once the collapse is completed, the spooky marks are replaced with real (classical) marks. Figure 4 shows the resulting position.

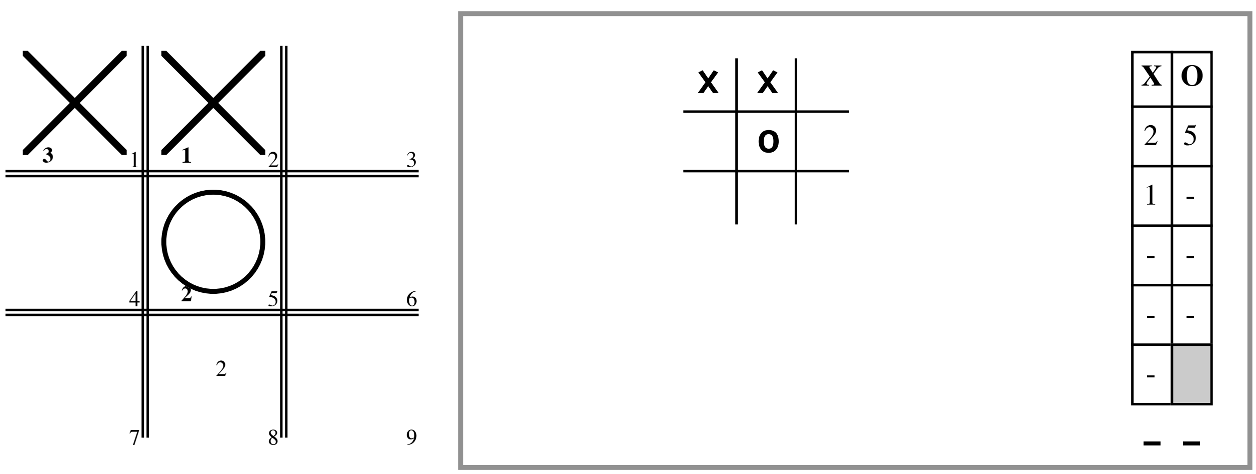

Figure 4: Collapse

Play can now proceed in other squares, but no more spooky marks can be placed in the collapsed squares (1, 2, 5). Recall that when a physical measurement is made, we only get classical values. We never directly observe superpositions, we must infer or calculate what the quantum states were. We know they are real since without them, we cannot correctly predict experimental results, but they elude direct detection. Therefore, we now have data, the collapsed positions of the first three moves of the game, and we can form a listing of the classical game that this quantum game yielded.

I. Analysis

Quantum Tic-Tac-Toe has yielded some two dozen metaphors with quantum mechanics. Given the simplicity of the rules, this suggests that something fundamental is being revealed by these abstract quantum systems. Table 2 lists the metaphors we have uncovered to date. While several characteristic features of real physical quantum systems are not listed, we believe that extending AQS to include complex superposition and conjugate variables will yield them. By initially excluding these aspects of quantum mechanics, the central role of self-reference is more easily seen.

Quantum Tic-Tac-Toe Metaphors with Quantum Physics	
Measurement events	**Delayed Choice experiment**
Cyclic entanglements	**Everett's Many Worlds Hypothesis**
Transition to classical states	**Quantum computing**
Reduction in the number of classical "universes"	**Present influenced by futures that never happen**
Superposition	**Present influenced by pasts that never happened**
Evolution/collapse duality	**Spooky action at a distance**
Determinism/non-determinism duality	**Macro measurement of a quantum object**
Correspondence principle	**Uncollapsed historical states**
Fuzziness of time in the present	**Quantum randomness**
Ascertainity principle	**Low entropy initial conditions**
Backwards in time causality	**Fine-tuning of the universal constants**
Decoherence	

TABLE 1. Metaphors with Quantum Physics Provided by Quantum Tic-Tac-Toe and Abstract Quantum Systems (AQS) in General.

Due to space limitations, we will discuss only one of these metaphors. The metaphor we are interested in is the implicit backwards-in-time causality exhibited by AQS. Consider, "What caused move one of the game to end up in square two instead of in square one?" Answer, move three did. A future event influenced a past event. Indeed, collapse of a cyclic entanglement is always backwards in time.

Figure 5 shows a dramatic situation where BTC is crucial to the tactics of the game. While this example was carefully constructed for pedagogical reasons, backwards-in-time causality is a fundamental feature of Quantum Tic-Tac-Toe and of AQS in general. Indeed, a winning strategy cannot be developed without it. The seven moves of this game have all been entangled in the center square and it is now O's move. In looking at the classical ensemble she notices that X has already won five of the eight games, in each case down the first column, and on move seven. Her only hope of winning is to find an entanglement that will make all five contradictory.

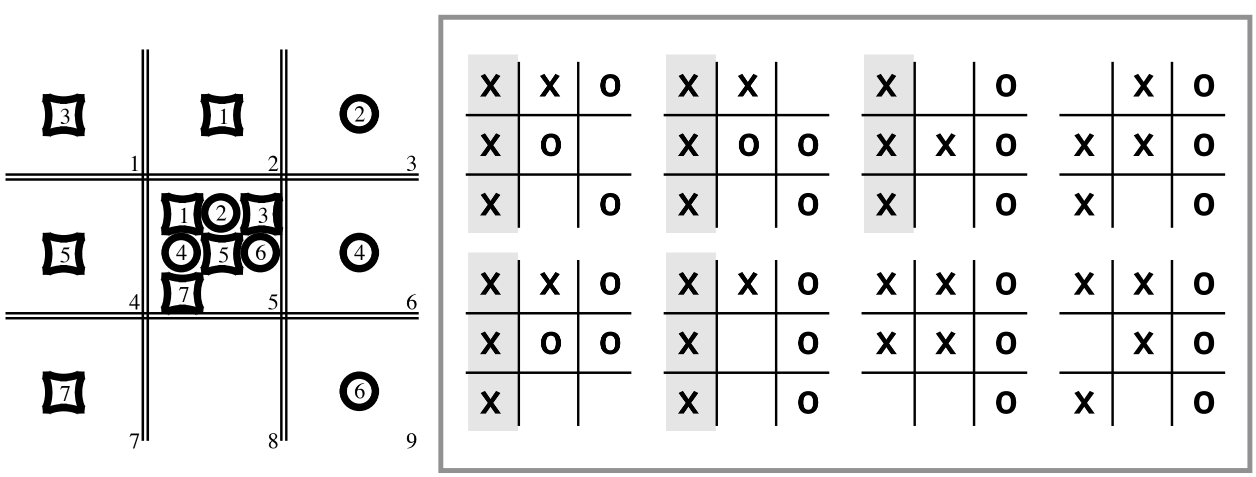

Figure 5: Backwards-in-Time Causality

It turns out she has three such moves. Figure 6 shows one of them.

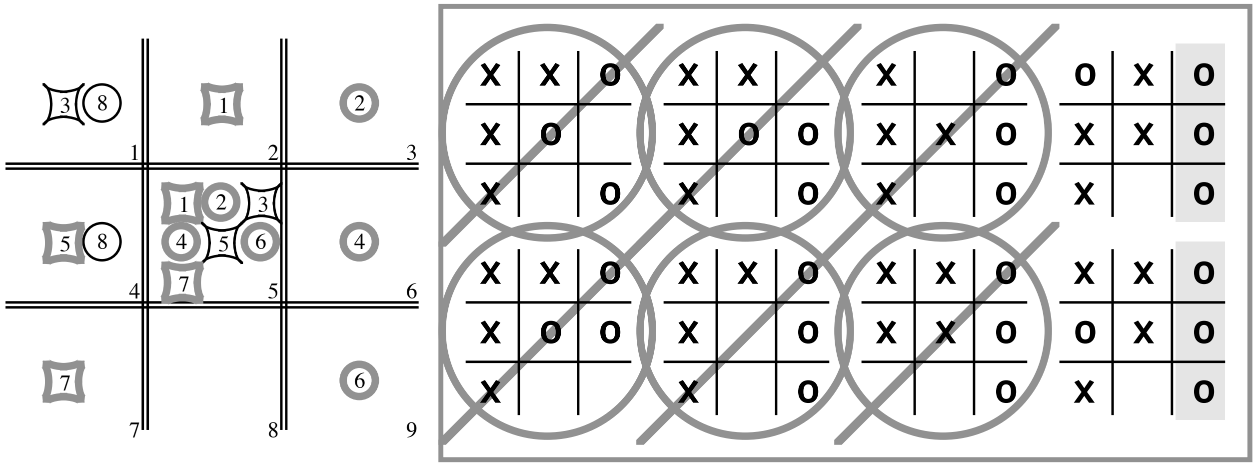

Figure 6: Temporal Paradox

As before, we have ghosted the moves on the cyclic entanglement, but we have also dimmed the moves that, while entangled with the cycle, are not actually in the cycle; they are called stems. O has succeeded in making all five of X's winning realities contradictory, indeed she has killed off six classical games. But that is not the best part. In both of the remaining classical games, she has a win in the right column; no matter what X does, she has won. And even that's not the best part. Her win occurs on move six!

Let's review. On time-step seven of the equivalent classical game, O detected a high likelihood of an undesirable outcome (X wins). She took action after this at time-step eight to make the bad things never happen, replacing them at time-step six, before they never happened, with an outcome favorable to her. The past has been influenced by the future. That sounds an awful lot like time travel. The causal chain of events unfolds in the quantum reality without ambiguity, but as seen from the classical viewpoint, the past has been changed.

Quantum Tic-Tac-Toe is a metaphor for a resolution of the measurement problem where collapse is induced by cyclic entanglements permitting paradox-free backwards-in-time causality. You can explore this resolution on the web at www.ParadigmPuzzles.com where you will find a Quantum Tic-Tac-Toe board that enforces the rules and shows the classical ensemble[18].

II. Implications

Abstract Quantum Systems have several implications for the foundations of quantum mechanics.

1. Cyclic entanglements offer a formal measurement mechanism that obviates the need for that hard-to-define observer. The self-reference in the cyclic entanglement is a natural source of nonlinearity and much less ad hoc than current efforts to add nonlinear terms to the Schrödinger equation.
2. This model suggests that there are disallowed vectors in the Hilbert space of a quantum system. When the system evolves to one of these disallowed vectors, a collapse occurs. The state collapses to one of the components of the system vector in whatever basis there exists a self-referential entanglement.
3. Until a collapse occurs, the past and future are not set; they form a malleable present. In quantum systems, the present is not an infinitely thin barrier between the past and the future; it has a "thickness." If, in a classical universe, the future hasn't happened yet, in a quantum universe neither has the present.
4. Collapse is always into the past. We saw hints of this in the previous paper. The symmetric spacetime interval connecting two entangled particles is always below the plane of simultaneity of their respective detections.
5. Even though the cyclic entanglements represent closed loops in time, temporal paradoxes are not permitted. All contradictions are automatically pruned from the classical ensemble. The pruning of contradictory classical realities is the censor mechanism that permits BTC, but prevents temporal paradox. A temporal paradox does what it was always feared it would do, it breaks the universe, but it only breaks a classical

one; as along as it does not break all the classical realities in the ensemble, the quantum universe persists. Therefore, temporal paradox is *not* a compelling argument against FTL achieved via quantum systems!

6. One argument against the possibility of an FTL technology is that there does not seem to be any natural FTL phenomena. If cyclic entanglement of quantum systems is the measurement mechanism, and if it always involves BTC as it does in AQS, then FTL phenomena are all around us – collapse of the wave function is an FTL event.
7. The concentration of information that occurs in the temporal indeterminacies comes from the classical realities that have been pruned from the classical ensemble. Realities that no longer exist have affected those that still do!
8. Since these cyclic entanglements span time, perhaps physical reality will support a limited but effective form of time travel, call it temporal spanning, that would permit some radical technological, military, and commercial applications.

III. Conclusion

The construction of a quantum system from a classical system is straightforward and uncomplicated. The addition of three types of rules suffices; rules of superposition, rules of entanglement, and rules of collapse. In the case of Quantum Tic-Tac-Toe, one of each is sufficient to produce an abstract quantum system (AQS) with enough fidelity to replicate many of the most fundamental attributes of physical quantum systems. The resulting model offers an observer-free measurement mechanism and through the classical ensemble presents an understandable explanation of how quantum physics can be as weird as it is. However, the model predicts more phenomena than have currently been observed in quantum systems, in particular backwards-in-time causality (BTC). Given the simplicity of AQS, it seems unlikely that real physical quantum systems can avoid these same phenomena. At worst, this model invites us to ask new questions of quantum systems that should lead to new discoveries. At best, this model predicts that physical reality can support BTC and therefore superluminal communications. If the scientific implications are exciting, the technological implications are astounding, one of which is explored in the next paper. At this time, we cannot rule out a limited, but viable form of time travel (temporal spanning) that may permit receiving information from the future and changing the past in paradox-free but non-trivial ways.

Acknowledgments

We wish to thank the management at Novatia, Inc. for their continued support of this research.

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