

Quantum Assisted Rendezvous¹²

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¹ J. Tucker et al., *New J. Phys.* **26**, 093038 (2024).

² J. Tucker et al., arXiv:2606.16784 (2026).

Acknowledgments (1)

Theory

Experiment

Collaborators: Chris Weeks, Peter Drmota, Ellis M. Ainley, Ayush Agrawal, Adam R. Martinez, Erin Malinowski, Jacob A. Blackmore, David P. Nadlinger, Gabriel Araneda, David M. Lucas, Carlos A. Perez-Delgado, Paul Strange, Jorge Quintanilla

QuARC



Acknowledgments (2)



PhD Funding

NISQ hardware time
through the IBM
researchers Program

NISQ hardware time
through SparQ Access

Contents

Einstein, Podolsky, and Rosen

Rendezvous

Conclusion

The Einstein, Podolsky, and Rosen Paradox

Einstein, Podolsky, and Rosen (EPR) aimed to prove that the theory of Quantum mechanics lacked completeness.



Albert Einstein



Boris Podolsky



Nathan Rosen

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues
Find It Is Not 'Complete'
Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of
'the Physical Reality' Can Be
Provided Eventually.

Entanglement shows instantaneous correlations but nothing can travel faster than light?¹

⇒ There must be “local hidden variables”

¹ A. Einstein, B. Podolsky, and N. Rosen. “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” In: *Phys. Rev.* (1935). DOI: 10.1103/PhysRev.47.777.

Nobel Prize



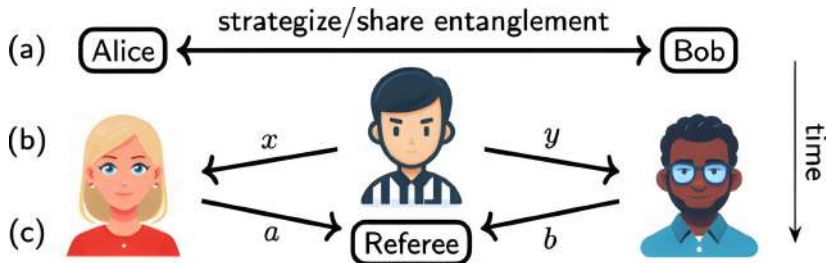
Bell developed a theorem that shows QM is not compatible with LHV theories^a.

^aJ. S. Bell. "On the Einstein Podolsky Rosen paradox". In: *Physics Physique Fizika* (1964). DOI: 10.1103/PhysicsPhysiqueFizika.1.195.

Experimentally verified by Alain Aspect, John F. Clauser, and Anton Zeilinger, which earned them the Nobel Prize in Physics^a.

^aFor experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science. Tech. rep. The Royal Swedish Academy of Sciences, 2022. URL: <https://www.nobelprize.org/prizes/physics/2022/advanced-information/>.

Incomplete Information Games



[Figure from Ref.¹

¹Peter Drmota, Dougal Main, EM Ainley, Ayush Agrawal, Gabriel Araneda, David P Nadlinger, BC Nichol, Raghavendra Srinivas, A Cabello, and DM Lucas. "Experimental quantum advantage in the odd-cycle game". In: *Physical Review Letters* 134.7 (2025), p. 070201.

Quantum Magic squares^{1,2}

An “impossible” magic square:

+1	+1	+1
-1	+1	-1
+1	?	+1

$$\prod_{\text{any row}} = +1 \qquad \prod_{\text{any column}} = -1$$

¹Theory: ND Mermin, PRL **65**, 3373 (1990) and A Peres, Phys. Lett. A **151**, 107 (1990).

²Experiment (photons): Jia-Min Xu et al., PRL **129**, 050402 (2022).

Quantum Magic squares^{1,2}

Let's gamify this: [Figure from Ref. 2]



- Referee asks Alice/Bob for a row/column.
- Answers must be consistent.

$$P_{win}^{classical} = 8/9$$

$$P_{win}^{quantum} = 1$$

Quantum strategy:

1. Prepare two entangled pairs:

$$|\Psi\rangle = (|00\rangle + |11\rangle) \otimes (|00\rangle + |11\rangle)$$

Alice holds 1st qubit of each pair,
Bob holds the 2nd qubit

2. Alice/Bob measure operators from the following table:

$I \otimes Z$	$Z \otimes I$	$Z \otimes Z$
$X \otimes I$	$I \otimes X$	$X \otimes X$
$-X \otimes Z$	$-Z \otimes X$	$Y \otimes Y$

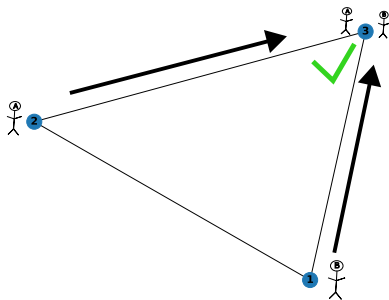
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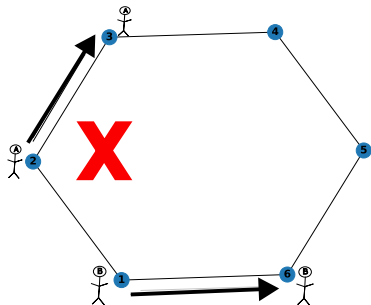
Can we use it?

Now we ask the question, are there potential applications that use this quantum phenomena?

Rendezvous



(a)

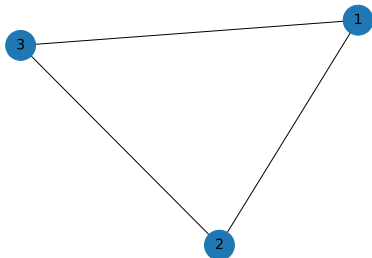


(b)

Uses in: distributed computing, communications and robotics.

Classical Strategies

- Optimal Classical Strategy is always deterministic!
- Can map these strategies to binary lists of actions
- Map 0 to go to lowest available index
- Map 1 to go to highest available index



Optimal Classical

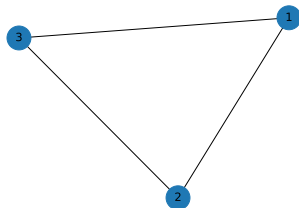
Take the strategy given by:

(0,0,0)

Represents the optimal strategy
known as go to lowest.

$$P_w = \frac{5}{9}$$

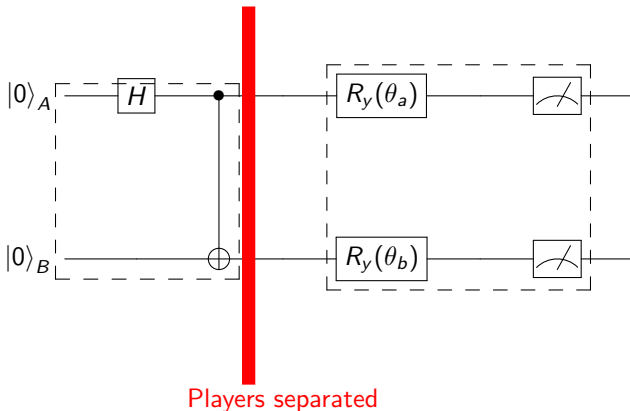
		Bob		
		1	2	3
Alice	1	W	L	L
	2	L	W	W
	3	L	W	W



What if we gave them Quantum Resources?

State Initialization

Local Player Actions



We can now build a strategy using the angles the players rotate by,

$$(\theta_1, \theta_2, \theta_3),$$

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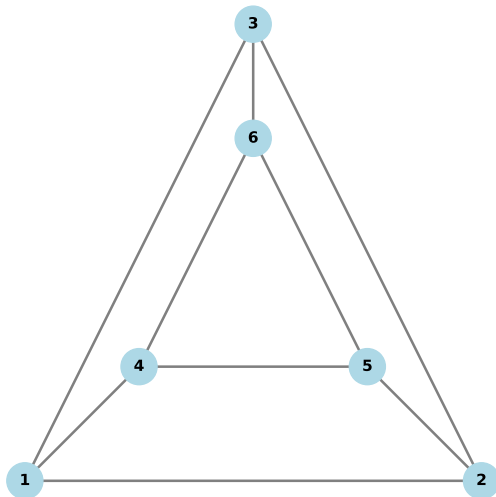
$$(0, \frac{\pi}{3}, \frac{2\pi}{3}),$$

To give a winning probability of,

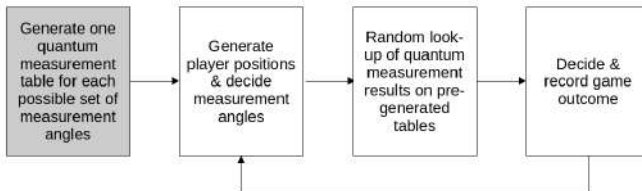
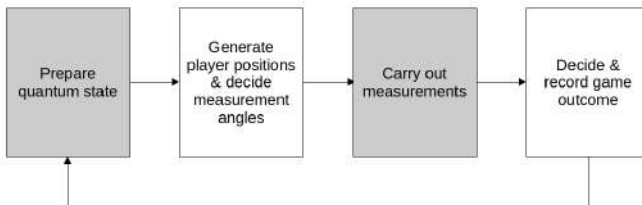
$$P_w = \frac{5}{9} + \frac{1}{36} \text{ } (\sim 3\% \text{ quantum advantage})$$

Quite a small advantage but expected from how simple the problem is.

We have found advantage up to 10% on the graph Y_3



How NISQ hardware simulations were carried out



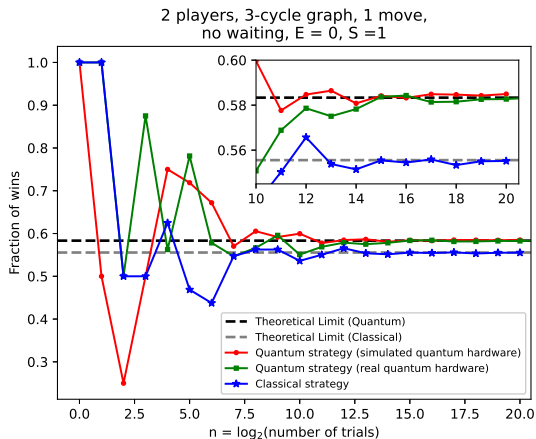


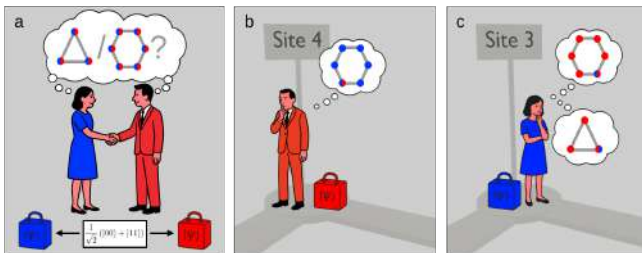
Figure: Explicit simulations of the rendezvous game being played using NISQ hardware¹

Three choice Simulation

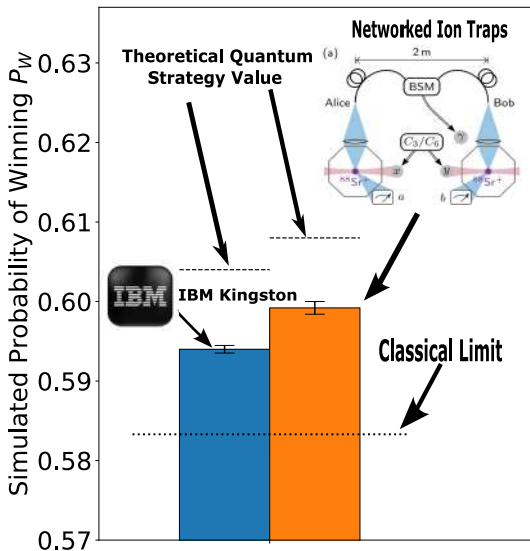
¹ Joshua Tucker, Paul Strange, Piotr Mironowicz, and Jorge Quintanilla. "Quantum-assisted rendezvous on graphs: explicit algorithms and quantum computer simulations". In: *New Journal of Physics* 26.9 (2024), p. 093038.

What if we remove certainty in the environment ?

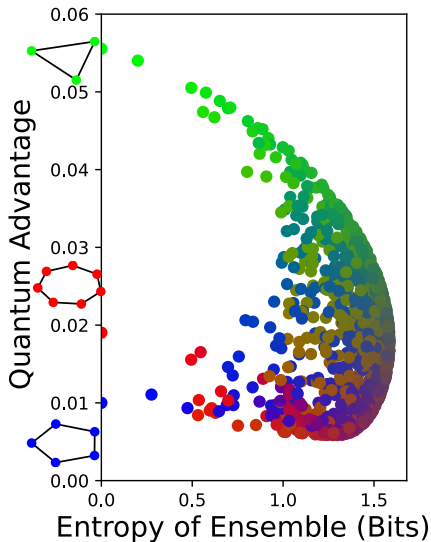
Differing amounts of local information



Maximally uncertain Ensemble of C_3 and C_6



Varying the Uncertainty



Conclusions

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- An Advantage can be gained through using entanglement as a resource in non-communication games
- While small to begin with we can find larger advantages by increasing the complexity of the problem
- Current NISQ hardware is able to obtain the quantum advantage in simpler models
- The advantage survives in topologically uncertain situations and increases when we give more local information

Thank you for listening :)



Quantum Assisted Rendezvous, J.
Tucker et al., *New J. Phys.* **26**, 093038
(2024).



Quantum Nonlocal Games on Graph
Ensembles, J. Tucker et al.,
arXiv:2606.16784 (2026).

Additional Slides

CHSH Inequality

Consider observables A, A' (Alice) and B, B' (Bob) that yield outcomes ± 1 . The CHSH quantity is:

$$S = AB - AB' + A'B + A'B' = A(B - B') + A'(B + B') \quad (1)$$

Classically: Since $B, B' \in \{-1, 1\}$, either $(B - B') = 0$ or $(B + B') = 0$. Thus $S = \pm 2$, giving the fundamental limit:

$$|S_C| \leq 2 \quad (2)$$

Quantum Mechanically: These become operators acting on a state $|\psi\rangle$. The expectation value is:

$$S_Q = \langle \psi | A \otimes B | \psi \rangle - \langle \psi | A \otimes B' | \psi \rangle + \langle \psi | A' \otimes B | \psi \rangle + \langle \psi | A' \otimes B' | \psi \rangle \quad (3)$$

Because quantum operators do not necessarily commute, this limit increases to:

$$|S_Q| \leq 2\sqrt{2} \quad (4)$$

3 choice strategy Y_3

$$|\psi\rangle_i = \frac{1}{\sqrt{3}} (|-1\rangle \otimes |-1\rangle + |0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle) \quad (5)$$

$$\hat{R}(\alpha, \beta, \gamma) = \begin{pmatrix} \cos \beta \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma \\ \cos \beta \sin \gamma & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma \\ -\sin \beta & \sin \alpha \cos \beta & \cos \alpha \cos \beta \end{pmatrix} \quad (6)$$

$$|\psi\rangle_f = \hat{R}(\alpha_a, \beta_a, \gamma_a) \otimes \hat{R}(\alpha_b, \beta_b, \gamma_b) |\psi\rangle_i \quad (7)$$

1. $S_z = -1 \rightarrow$ move to the adjacent vertex with the lowest label
2. $S_z = 0 \rightarrow$ move to the adjacent vertex with the middle-sized label
3. $S_z = 1 \rightarrow$ move to the adjacent vertex with the highest label.

3 Choice Simulation of $2K_4$

