Graphing the Mermin-Peres Magic Square

Calder Evans

Joint work with Dr. Samuel Harris and Taylor Smith

Northern Arizona University
Department of Mathematics and Statistics

SUnMaRC
13 April 2025

Department of Mathematics and Statistics

Presentation Outline

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2. Overview Non-local games
3. Explain the Mermin-Peres Magic Square Game
4. Define Graphs and Coloring

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- built a graph based on the game algebra of the Mermin-Peres Magic Square Game
  - We chose the Mermin-Peres game because it is the smallest synchronous game that has a winning quantum strategy but no classical strategy
- encoded the graph into SageMath and ran a multitude of constructions to identify which vertices could be removed without changing the colorabilities of the graph

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  - i.e. $P_A(a|x) = \sum_{b \in \mathcal{O}} P(a, b|x, y)$ is independent of y, and $P_B(b|y) = \sum_{a \in \mathcal{O}} P(a, b|x, y)$ is independent of x.

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  - i.e. If they give different answers they lose

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Definition

The Mermin-Peres Magic Square Game is a synchronous non-local game. In this game, Alice and Bob will each receive one equation from the following list:

$$x_1 + x_2 + x_3 \equiv 0 \pmod 2$$

$$x_4 + x_5 + x_6 \equiv 0 \pmod 2$$

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Alice and Bob fill out their assigned equations with 0's and 1's simultaneously without knowing how the other fills theirs out. Their goal is to satisfy each of their own equations while producing the same value for any shared variable.

Magic Square Representation

The Magic Square game can be represented by a 3x3 grid by labeling each cell like so:

x_1	x_2	x_3
x_4	x_5	x_6
x_7	x_8	x_9

$$x_1 + x_2 + x_3 = 0$$

$$x_4 + x_5 + x_6 = 0$$

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$$x_1 + x_4 + x_7 = 0 \qquad x_2 + x_5 + x_8 = 0 \qquad x_3 + x_6 + x_9 = 1$$

Magic Square Walkthrough

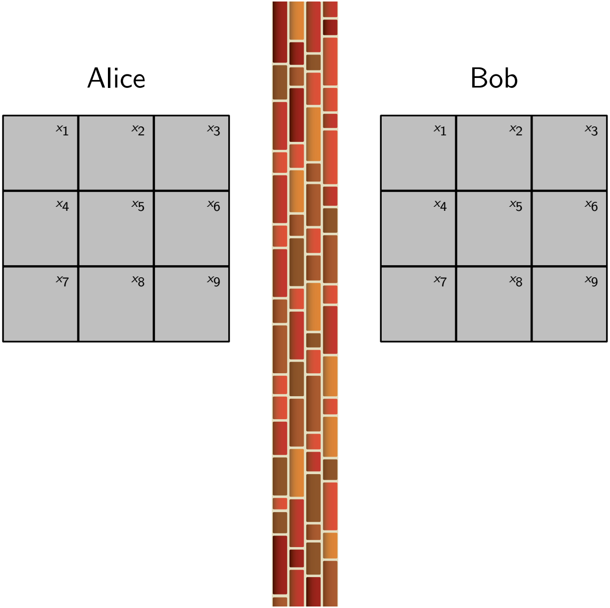
Alice

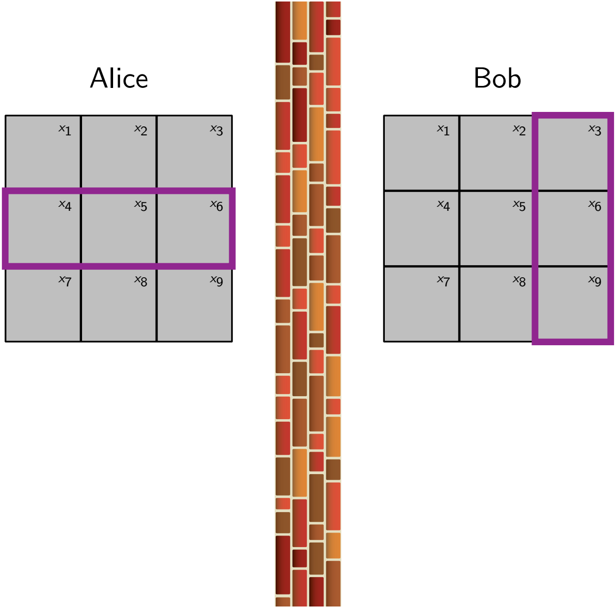
x_1	x_2	x_3
x_4	x_5	x_6
x_7	x_8	x_9

Bob

x_1	x_2	x_3
x_4	x_5	x_6
x_7	x_8	x_9

Magic Square Walkthrough




Alice
x_1 x_2 x_3
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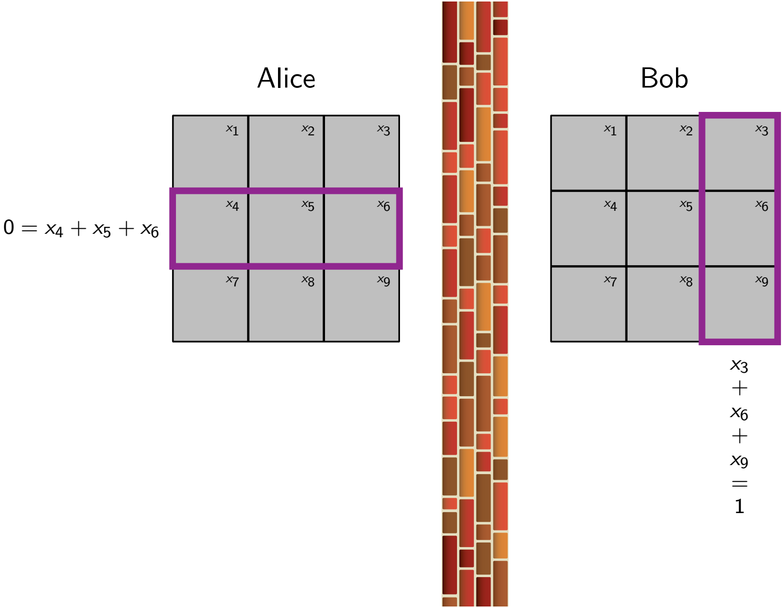

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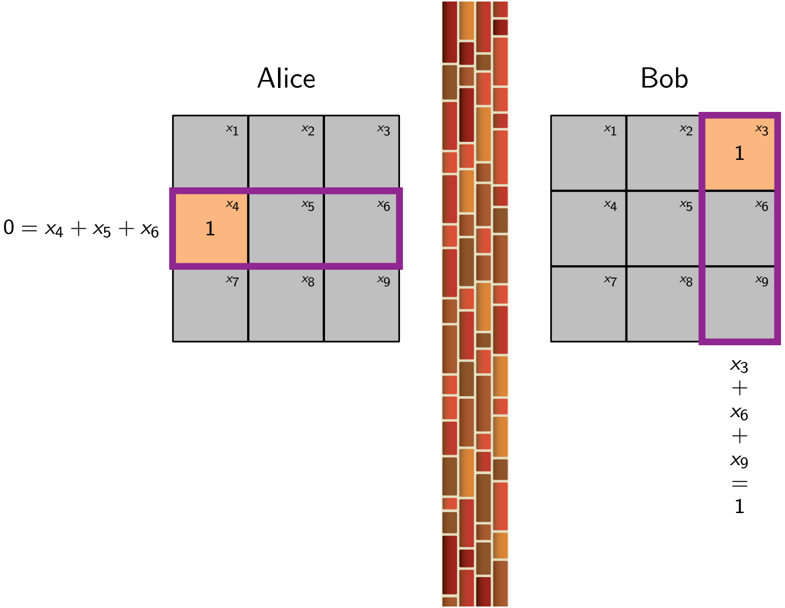

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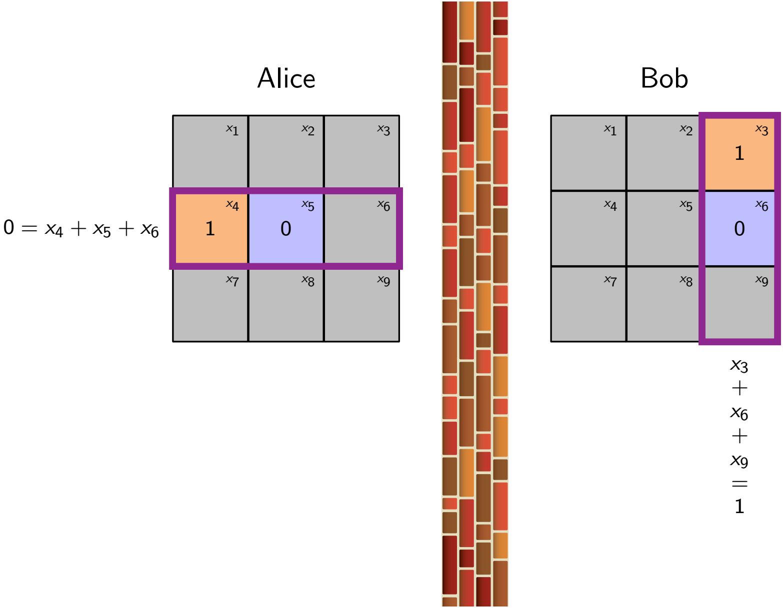

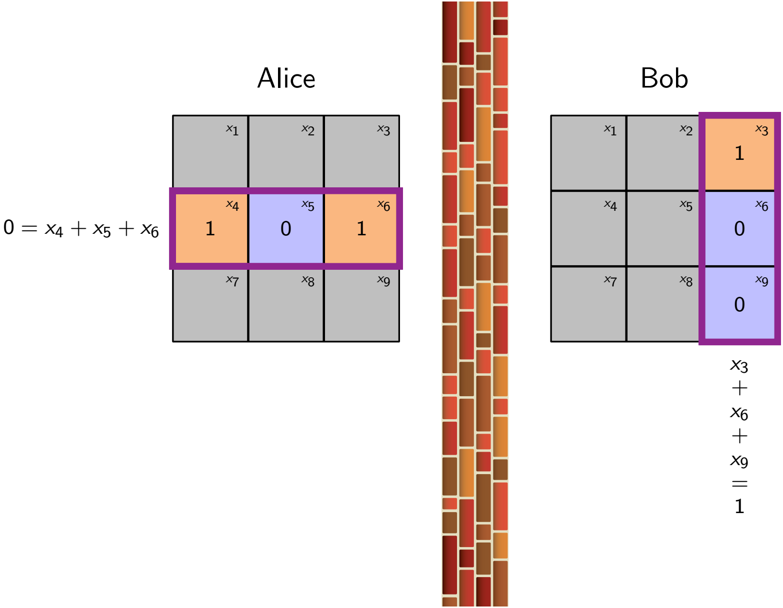
Alice
Bob
$0 = x_4 + x_5 + x_6$
x_1
x_2
x_3
x_4
x_5
x_6
x_7
x_8
x_9
1
0
1
x_1
x_2
x_3
x_4
x_5
x_6
x_7
x_8
x_9
1
0
0
$x_3 + x_6 + x_9 = 1$

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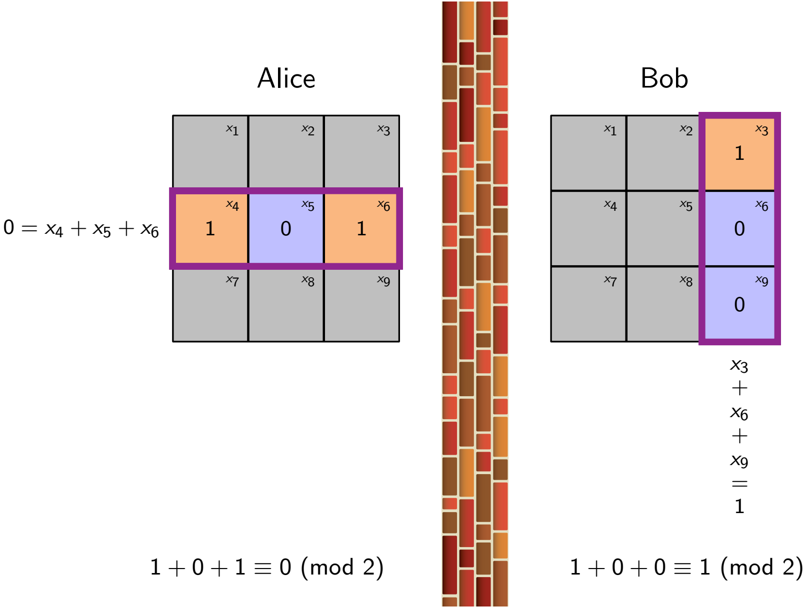


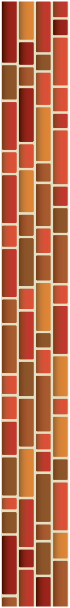
Alice

$0 = x_4 + x_5 + x_6$

x_1	x_2	x_3
x_4 1	x_5 0	x_6 1
x_7	x_8	x_9

✓

$1 + 0 + 1 \equiv 0 \pmod 2$



Bob

x_1	x_2	x_3 1
x_4	x_5	x_6 0
x_7	x_8	x_9 0

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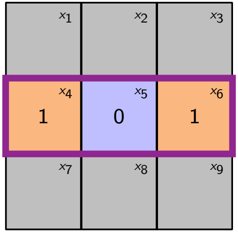

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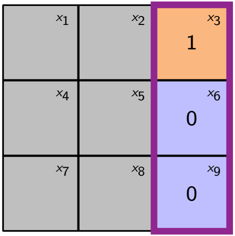

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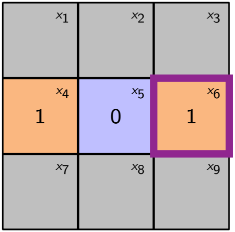

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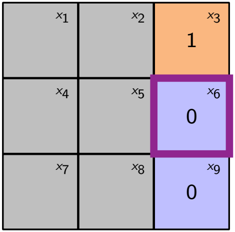
Bob



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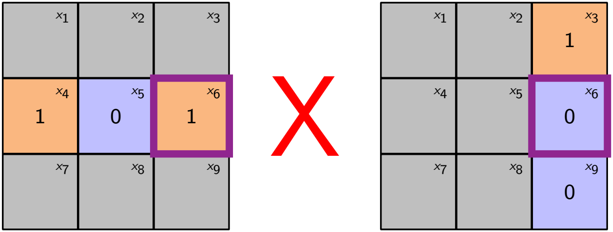

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Magic Square Walkthrough

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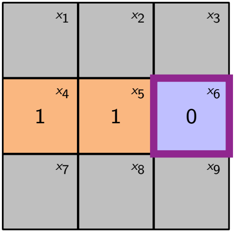
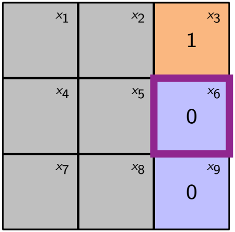


✓

$1 + 1 + 0 \equiv 0 \pmod 2$

Bob



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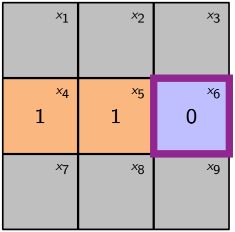

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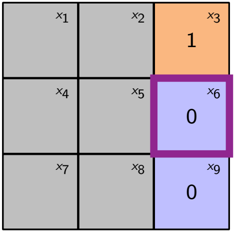
Bob



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Classical Strategy for Magic Square Game Strategy

Definition

A classical strategy for a Non-Local Game is represented by a function $f : \mathcal{I} \to \mathcal{O}$.

For the Magic Square Game, we can define a classical strategy using the grid below. The best strategy has them agree upon a set table of answers, this allows them to win most of the time. It is impossible to create a solution set that satisfies all nine equations at the same time, otherwise they would be able to win every single game.

x_1: 1	x_2: 0	x_3: 1	$1 + 1 = 0$
x_4: 1	x_5: 1	x_6: 0	$1 + 1 = 0$
x_7: 0	x_8: 1	x_9: 0	$\mathbf{1 \neq 0}$
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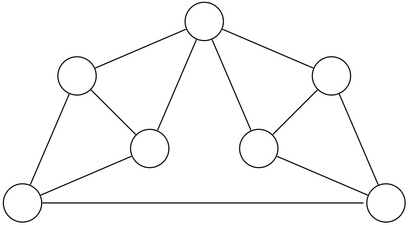

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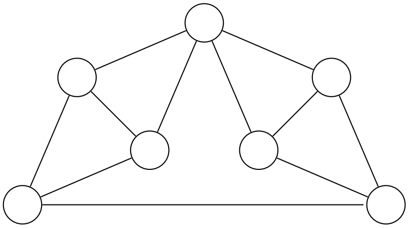

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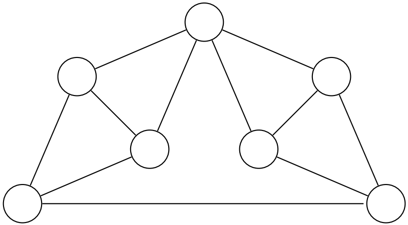

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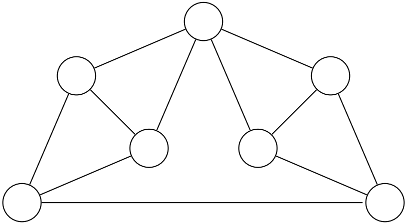

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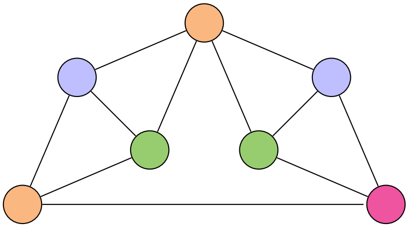
- We say that a graph is k-colorable if the minimum amount of colors needed to color the graph is at most k.



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Winning Mermin-Peres in Quantum (abridged)

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  - Matrices $e_{a,x}$ in $M_d(\mathbb{C})$ (matrices) (for some d), where $1 \leq x \leq 6$ and a ranges over solutions to equation x from Mermin-Peres, such that:

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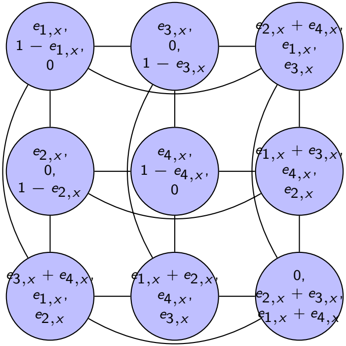
  - If $1 \leq x, y \leq 6$ and a is a solution to equation x, b is a solution to equation y, and a, b are inconsistent, then $e_{a,x} \cdot e_{b,y} = 0$.

You can transform any non local synchronous game into a 3 coloring game. We are doing a transformation like this for Mermin-Peres



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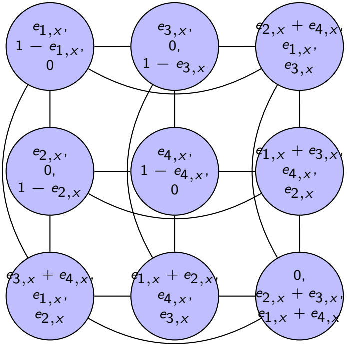
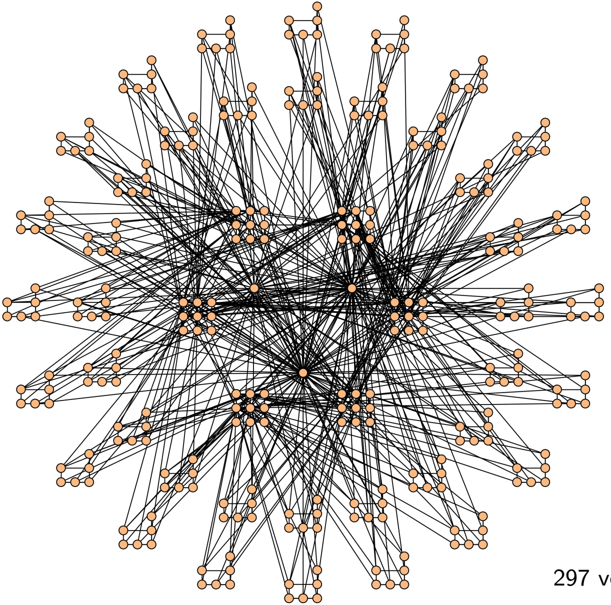


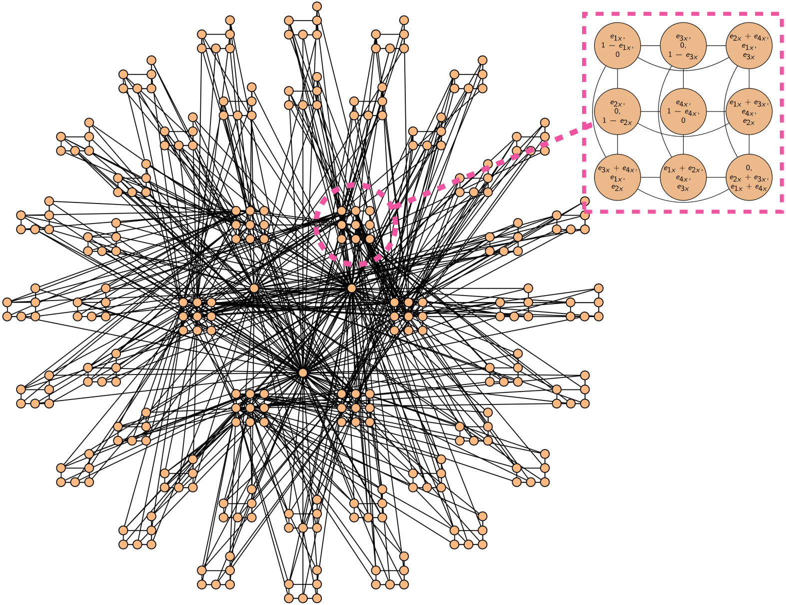
In quantum coloring, each vertex is colored with 3 projections that sum to 1 instead of a single color. These act on a shared entangled state, allowing Alice and Bob to coordinate their responses even when they are separated.

Mermin-Peres Graph



297 vertices

Mermin-Peres Graph



Thank you!

Questions?

Graph Coloring and Representations

Taylor Smith

Joint work with Dr. Samuel Harris and Calder Evans

Northern Arizona University
Department of Mathematics and Statistics

SUnMaRC
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NORTHERN ARIZONA UNIVERSITY
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3. How our graph is Quantum 3-Colorable and not Classically 3-Colorable

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2. Explain quantum coloring and encoding of game rules
3. How our graph is Quantum 3-Colorable and not Classically 3-Colorable
4. Share progress with whittling down our graph

Game Algebra

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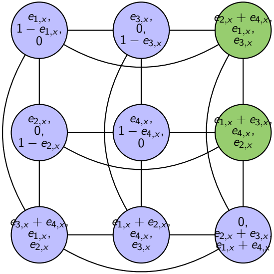
Example

$$(e_{2,x} + e_{4,x}, e_{1,x}, e_{3,x}) \cdot (e_{1,x} + e_{3,x}, e_{4,x}, e_{2,x})$$
$$= ((e_{2,x} + e_{4,x})(e_{3,x} + e_{1,x}), e_{1,x}e_{4,x}, e_{3,x}e_{2,x})$$
$$= (0, 0, 0).$$



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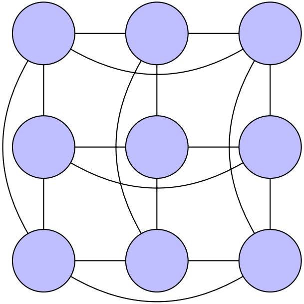

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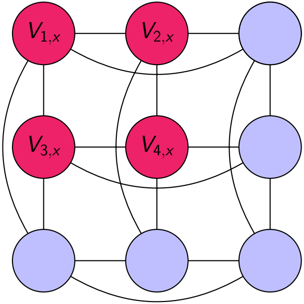

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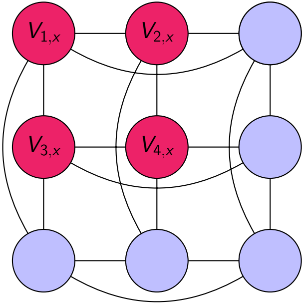

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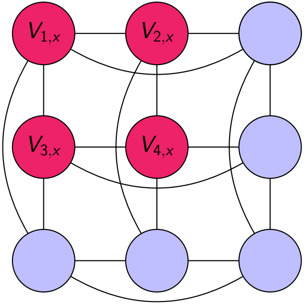
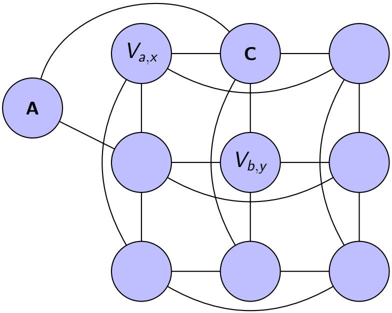
- Other Gadgets such as E_λ and F_λ subgraphs enforce the graph to not be classically 3-colorable.
- We call $V_{a,x}$ and $V_{b,y}$ incompatible whenever $\lambda(a, b, x, y) = 0$.

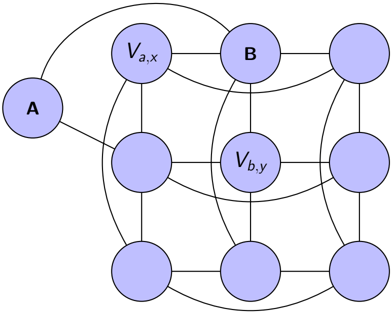


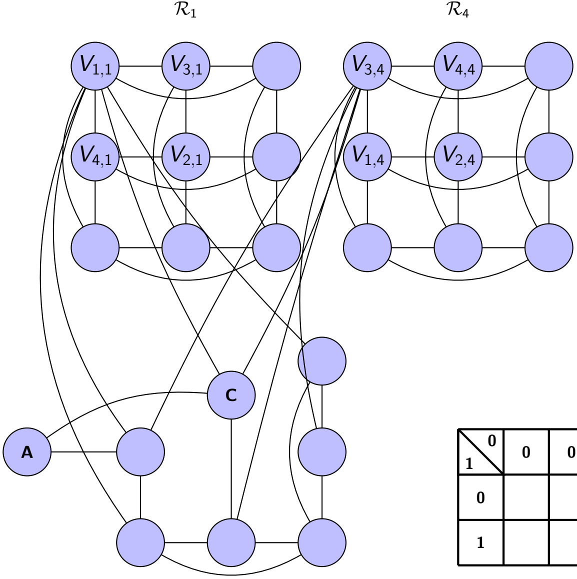
For vertices $V_{a,x}$ and $V_{b,y}$ who are incompatible, $\lambda(a,b,x,y) = 0$, and are not orthogonal to one another we create one of the subgraphs,

if $(a,b,x,y) \in \mathcal{E}_\lambda$



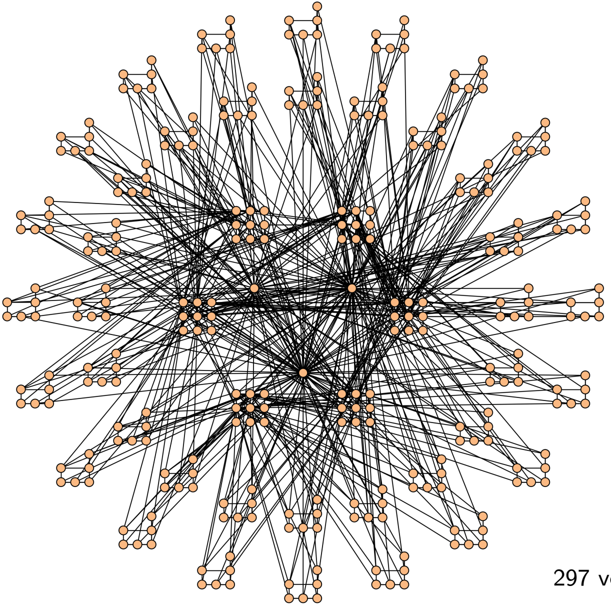
if $(a,b,x,y) \in \mathcal{F}_\lambda$



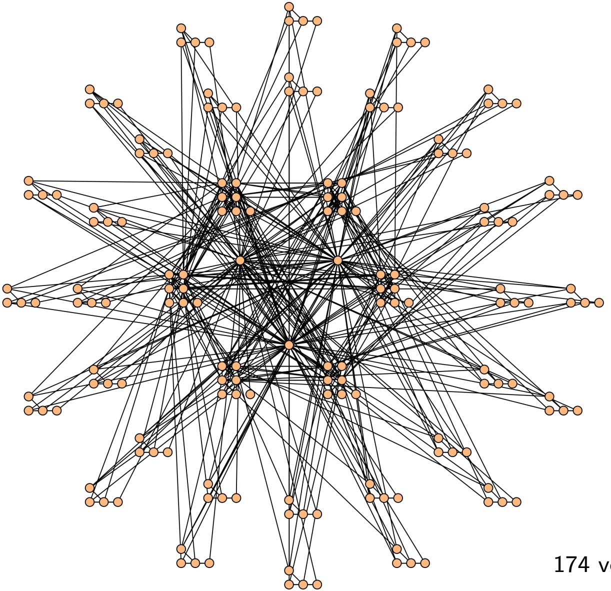


1 \ 0	0	0
0		
1		

Original Graph

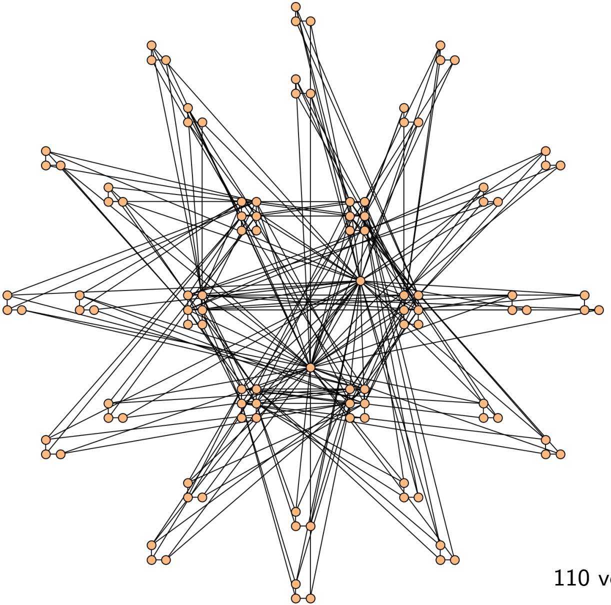


297 vertices



174 vertices

Final Reduced Graph



110 vertices

Thank you!

Questions?