Title: Gong Show

Speakers:

Collection: Foundations of Quantum Computational Advantage

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Abstract: IN PERSON - Lorenzo Catani, Matthew Fox, Hlér Kristjánsson, Gabrielle Tournaire

VIRTUAL - Jonte Hance, Sidiney Montanhano, Shiroman Prakash, Amr Sabry

Gong Show Presentations
Tuesday, April 30th, 2024

FoQaCiA

Workshop

In person:

Lorenzo Catani

Matthew Fox

Hlér Kristjánsson

Gabrielle Tournaire

Virtual:

Jonte Hance

Sidiney Montanhano

Shiroman Prakash

Amr Sabry

Funded by the European Union

NSERC CRSNG

Alternative robust ways of witnessing nonclassicality in the simplest scenario

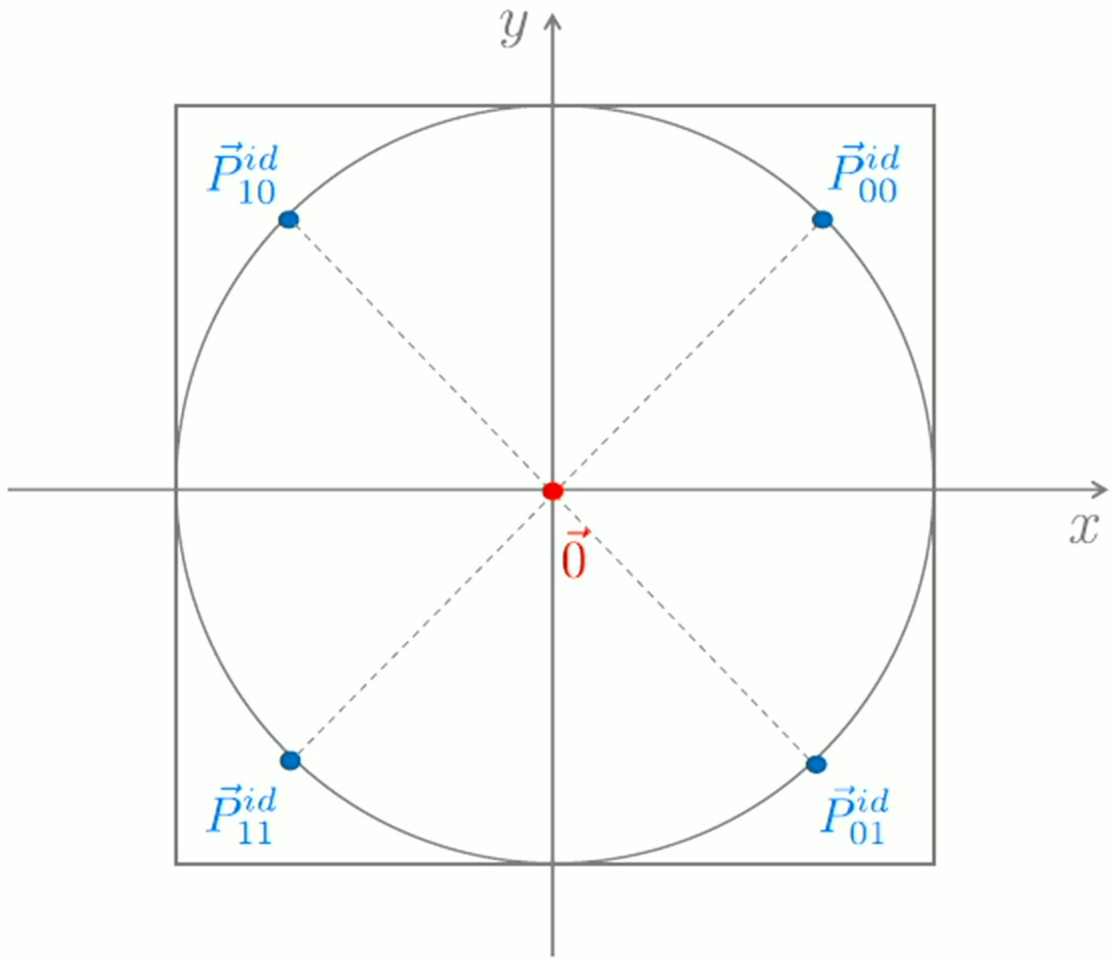
FoQaCia conference, Waterloo - 30/04/2024

Lorenzo Catani

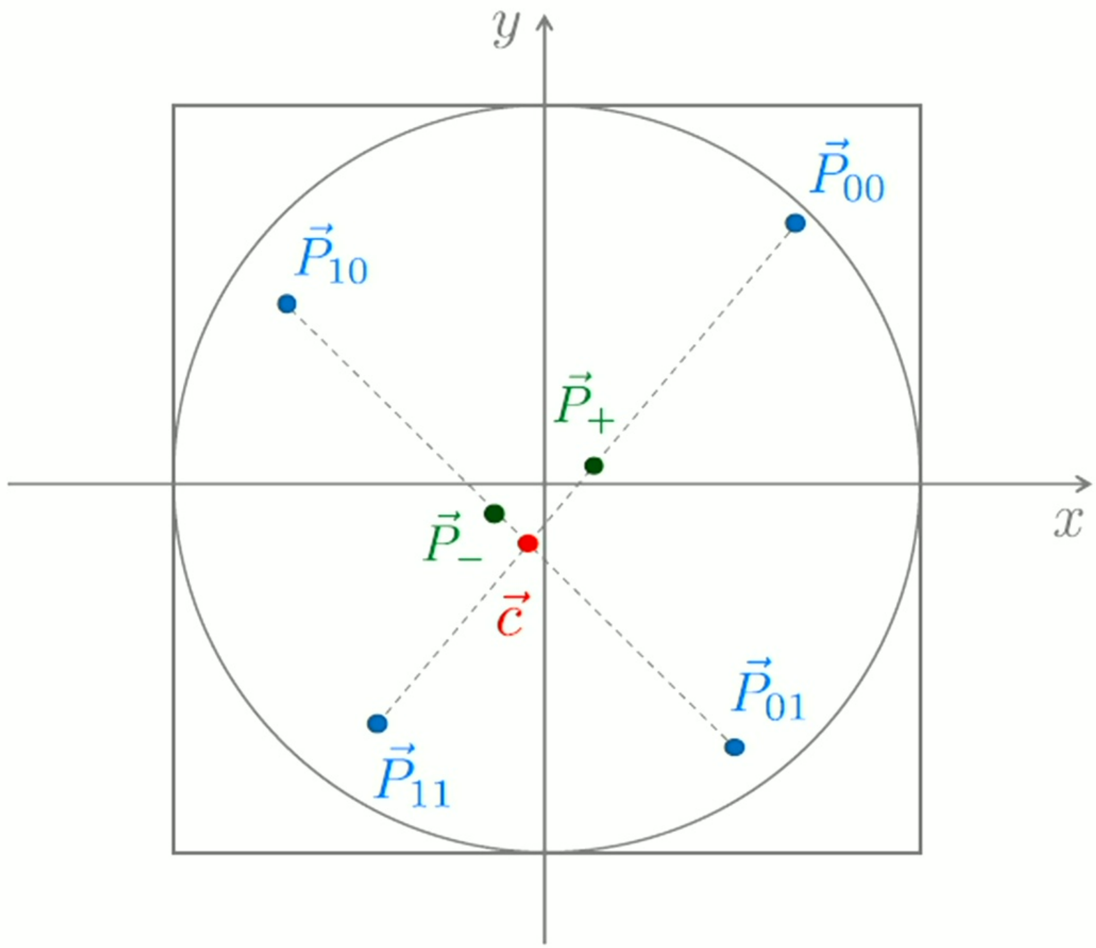
Joint work with Massy Khoshbin and Matt Leifer

PRA **109**, 032212 (2024)

Simplest Scenario – Ideal Case



Simplest Scenario – Realistic Case



Summary of Results

Approach	Notion of nonclassicality	Reference to *a priori* ideal preparations	Noise threshold of violation
Pusey's	Preparation contextuality	No	$\delta \leq 0.06$
Marvian's	Preparation contextuality	No	$\delta \leq 0.1$
Our work	Violation of BOD	Yes	$\delta \leq 0.007$

M. F. Pusey, Phys. Rev. A 98, 022112 (2018).
I. Marvian, arXiv:2003.05984v1 (2020).
A. Chaturvedi and D. Saha, Quantum 4, 345(2020).

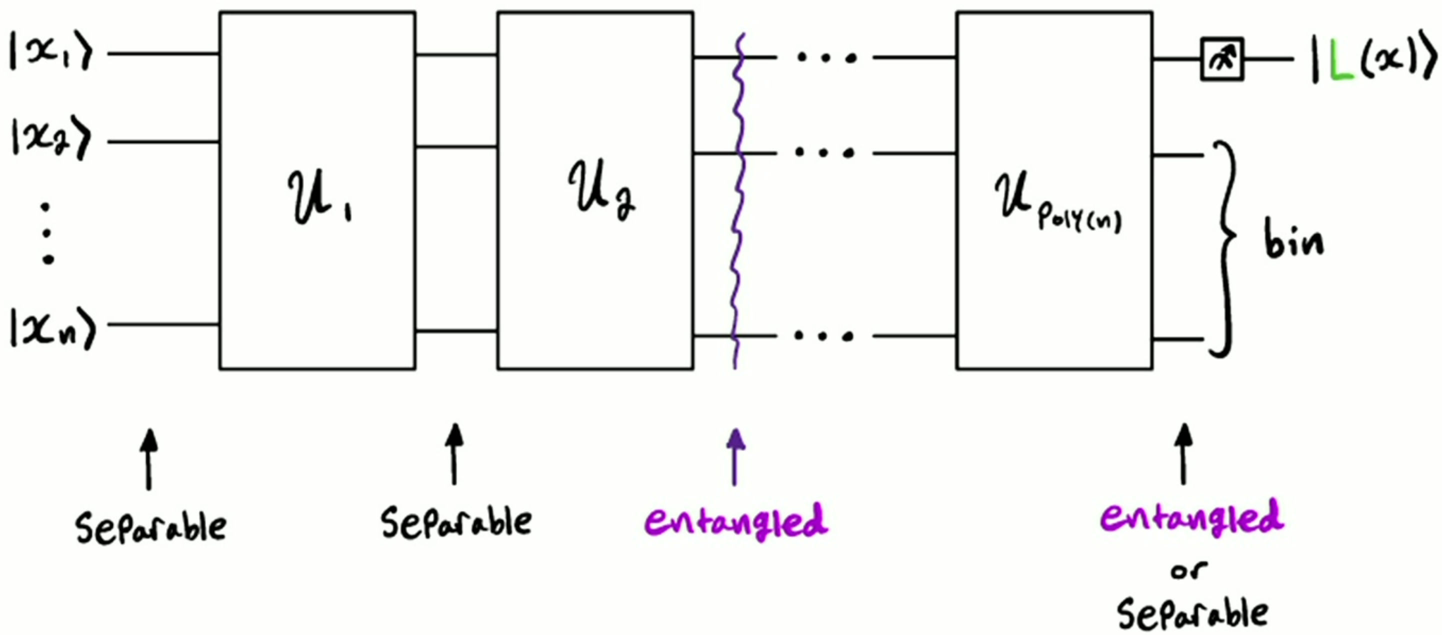
Is Entanglement Necessary for

BPP ≠ BQP?

Matthew Fox

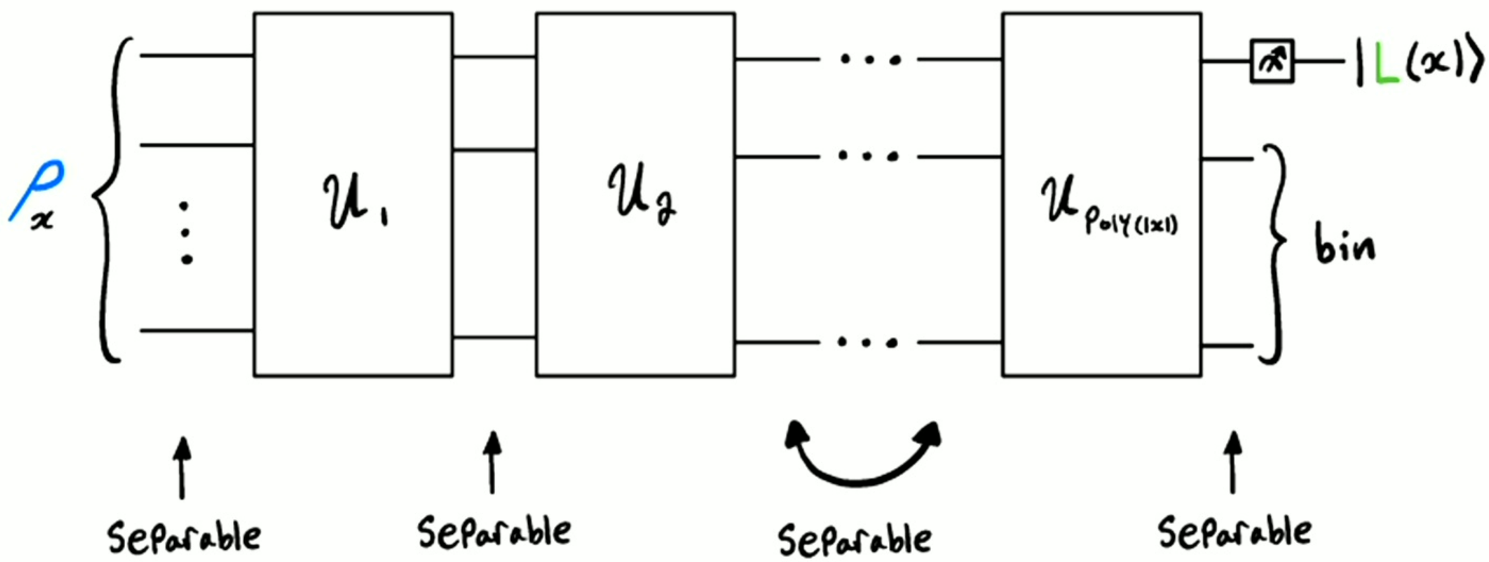
University of Colorado Boulder

Q: Does every (uniform, poly-size) circuit for $L \in BQP \setminus BPP$ necessarily entangle its input?



Q: Decide $L \in BQP \setminus BPP$ like this?

$x \rightarrow$ BPP Machine $\rightarrow y$ w/ $P_x(y) \rightarrow \underbrace{\sum_y P_x(y) |y\rangle\langle y|}_{\rho_x}$



Def: $L \in BQP_{sep}$ iff $L \in BQP$ and "entanglement is not necessary to decide L".

Basic Properties:

- $BPP \subseteq BQP_{sep} \subseteq BQP$
- $BPP = BQP_{sep}$ → "entanglement necessary"
- $BQP_{sep} = BQP$ → "entanglement NOT necessary"

Some Complexity Questions:

- $BPP \stackrel{?}{=} BQP_{sep}$
- $PostBQP_{sep}$ and PH collapse?
- Deferred Measurements in BQP_{sep}
- Non-entangling oracles

Thank You!

Slides ⟶

Universal algorithm for transforming Hamiltonian eigenvalues

arXiv:2312.08848

Tatsuki Odake[1], Hlér Kristjánsson[2,3,1], Philip Taranto[1] and Mio Murao[1]

1. The University of Tokyo
2. Perimeter Institute for Theoretical Physics
3. Institute for Quantum Computing, University of Waterloo

東京大学 THE UNIVERSITY OF TOKYO

PERIMETER INSTITUTE

IQC Institute for Quantum Computing

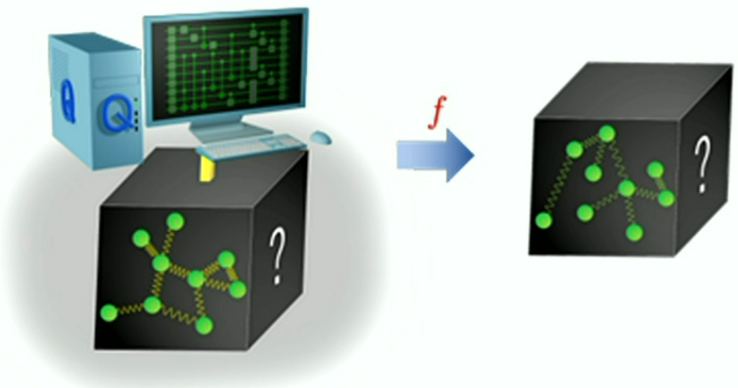
Simulating quantum systems

- So far: given classical description of Hamiltonian, simulate its dynamics[1]

$$H = \sum_j h_j H_j \quad \Rightarrow \quad U = e^{-iHt}$$

- Here: given **black-box** access to Hamiltonian dynamics, simulate a **functional transformation** of the Hamiltonian dynamics

$$e^{-iHt} \quad \Rightarrow \quad e^{-if(H)t'}$$

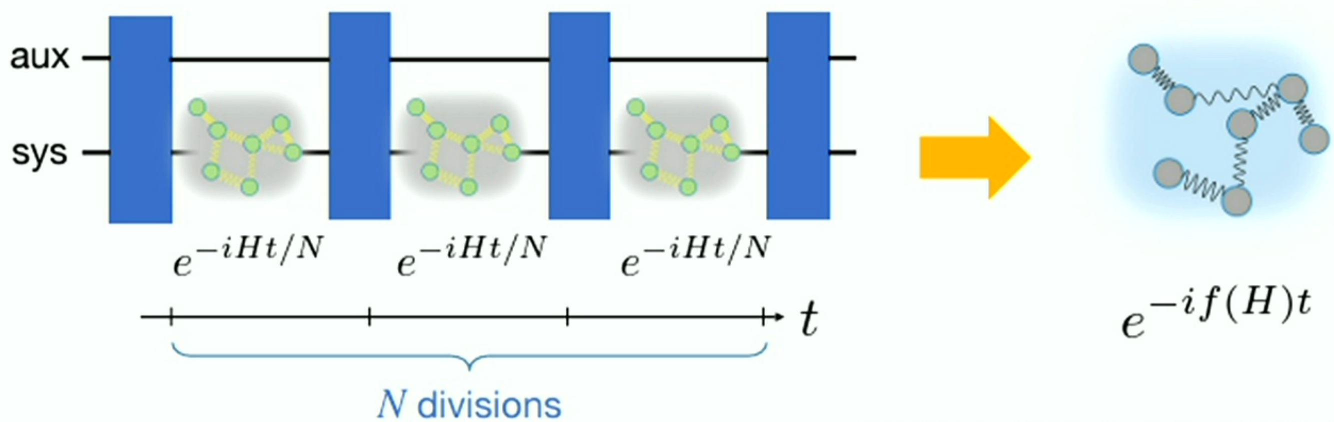


[1] e.g. Berry et al., *PRL*, 2015; Low & Chuang, *PRL*, 2017; Campbell, *PRL*, 2019

Higher-order transformations of Hamiltonian dynamics

Functional transformations of Hamiltonian dynamics can be achieved using **higher-order quantum computation** [1]

- Universal transformation of the **eigenvalues of any Hamiltonian (energy levels)** by any sufficiently differentiable function $f(H)$:
- Deterministic and ϵ-approximate with time complexity $\underbrace{O\left(\frac{t^6}{\epsilon^6}\right)}_{\text{preprocessing}} + \underbrace{O\left(\frac{t^2 n}{\epsilon}\right)}_{\text{main process}}$

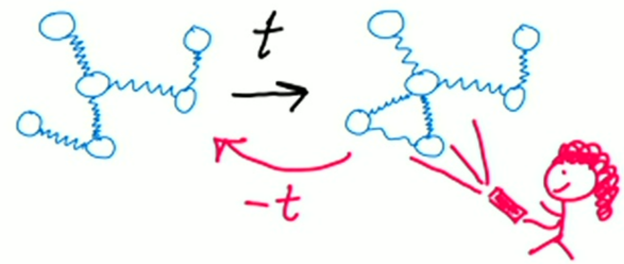


[1] Chiribella, D'Ariano, Perinotti, *PRL*, 2008

Functional programming approach

1. Simulate the **negative-time evolution** [1]:

$$e^{-iHt} \rightarrow e^{+iHt'}$$



Can be done without any additional auxiliary qubits!

2. Simulate the **controlled dynamics** [2]

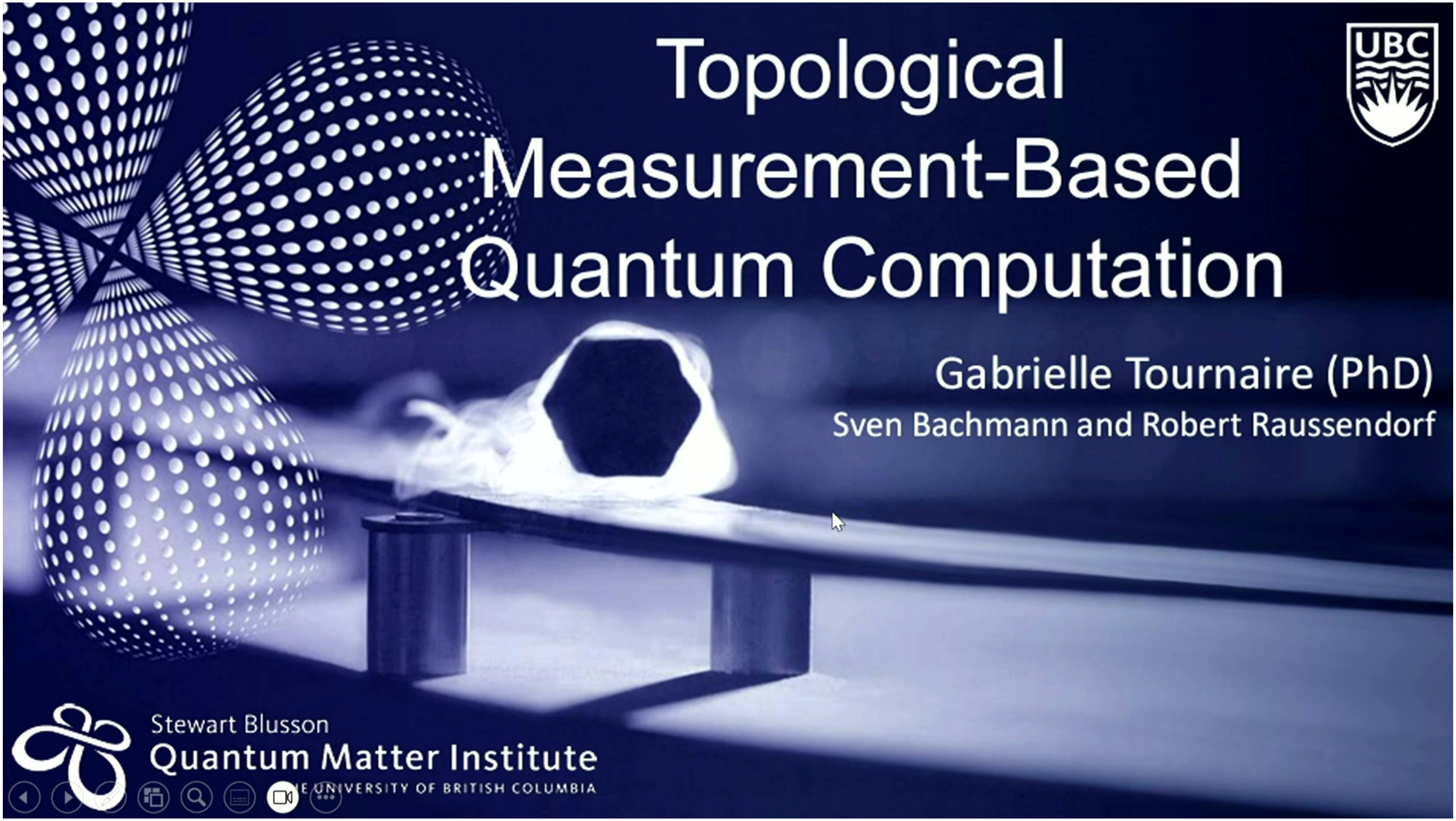
$$e^{\pm iHt} \rightarrow |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes e^{\pm iHt}$$

3. Simulate the **Fourier series** of the function f

$$|0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes e^{\pm iHt} \rightarrow e^{-if(H)t'}$$

4. **Compile** the randomisation in each step globally to improve time complexity

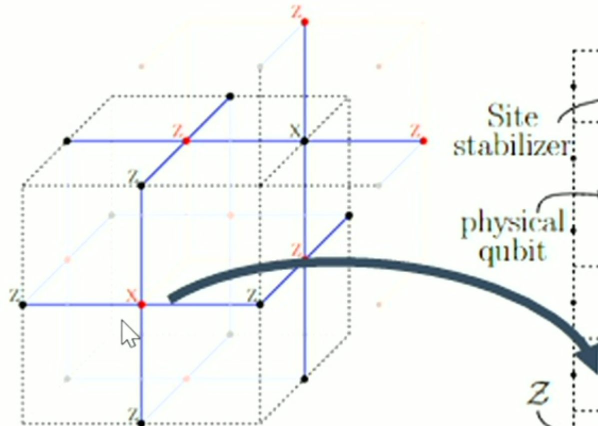
[1] Odake, Kristjánsson, Soeda, Murao, *PRR*, 2022. [2] Dong, Nakayama, Soeda, Murao, *arXiv*, 2019
see also: **QSVT**, e.g. Low & Chuang, *Quantum*, 2019


Topological
Measurement-Based
Quantum Computation
Gabrielle Tournaire (PhD)
Sven Bachmann and Robert Raussendorf
UBC
Stewart Blusson
Quantum Matter Institute
UNIVERSITY OF BRITISH COLUMBIA

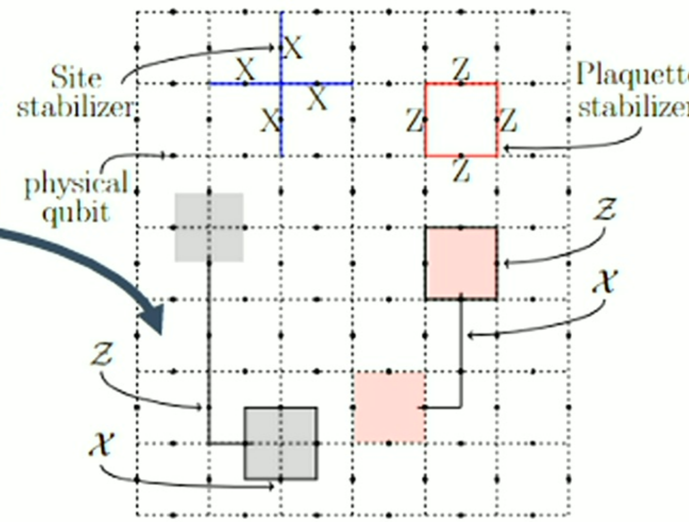
MEASUREMENT BASED QUANTUM COMPUTATION

- 3D cluster state lattice:
  - Black qubits on primal edges and dual faces
  - Red qubits on primal faces and dual edges
  - Stabilizers on primal and dual surfaces
- Measurement in the bulk = Toric code on the surface:
  - Cluster face = Toric code plaquette
  - X measurements: Toric code stabilizers
  - Z measurements: "holes" encoding logical qubits
- Processing information from one Toric code to another:
  - Different measurement patterns in the bulk.
  - Pauli and CNot gates topologically
  - Universality by magic state injection

3D cluster state unit cell:



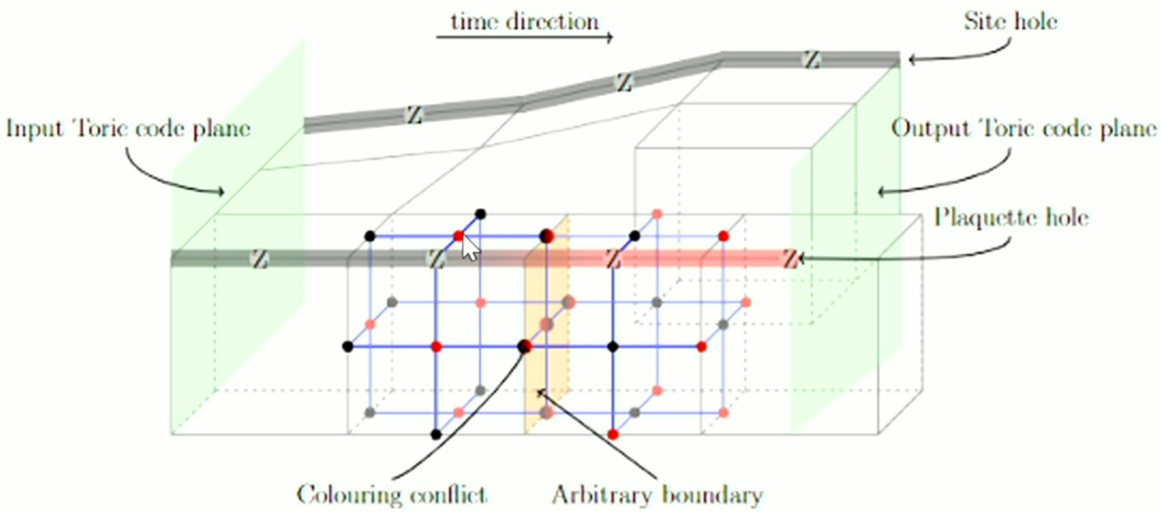
Logical qubits in the Toric code:



3D cluster state stabilizers:

$$K(c_2) = X(c_2)Z(\partial c_2)$$
$$K(\bar{c}_2) = X(\bar{c}_2)Z(\partial \bar{c}_2)$$

TWIST DEFECT: THE HADAMARD GATE



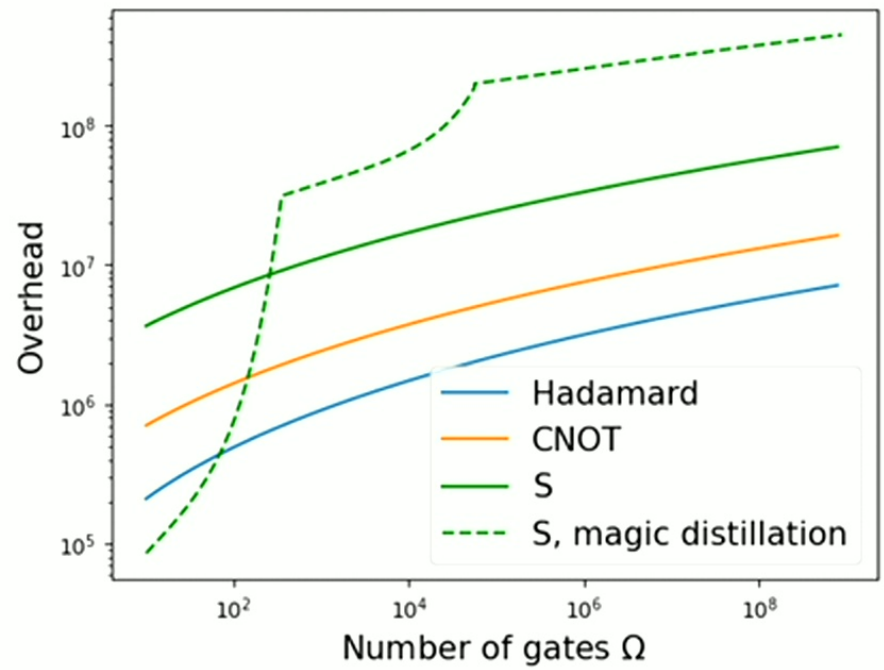
Twist defect: Sites holes ↔ Plaquette holes

- Dislocation defect
- Bi-coloring conflict
- Arbitrary boundary where the hole line changes type:
  - Site ↔ Plaquette
  - $\mathcal{X}_{primal} \longleftrightarrow \mathcal{Z}_{dual}$
  - $\mathcal{Z}_{primal} \longleftrightarrow \mathcal{X}_{dual}$

- ➔Hadamard gate
- Topological Clifford group
  - Paulis, CNot, Hadamard, S

OPERATIONAL OVERHEAD AND CLIFFORD GATES

- Operational cost of a gate
- Number of necessary operations vs number of gates in the circuit
- Low overhead for Hadamard and CNot
- S gate:
  - Hadamard defect yields one order of magnitude improvement
  - Kinks = another round of distillation



Stewart Blusson
Quantum Matter Institute

Measurement Back Action causes the difference between Classical and Quantum Counterfactual Effects

Jonte R Hance[1,2], Tomonori Matsushita[3], Holger F Hofmann[3]

[1] School of Computing, Newcastle University, 1 Science Square, Newcastle upon Tyne, NE4 5TG, UK

[2] Quantum Engineering Technology Laboratories, Department of Electrical and Electronic Engineering, University of Bristol, Woodland Road, Bristol, BS8 1US, UK

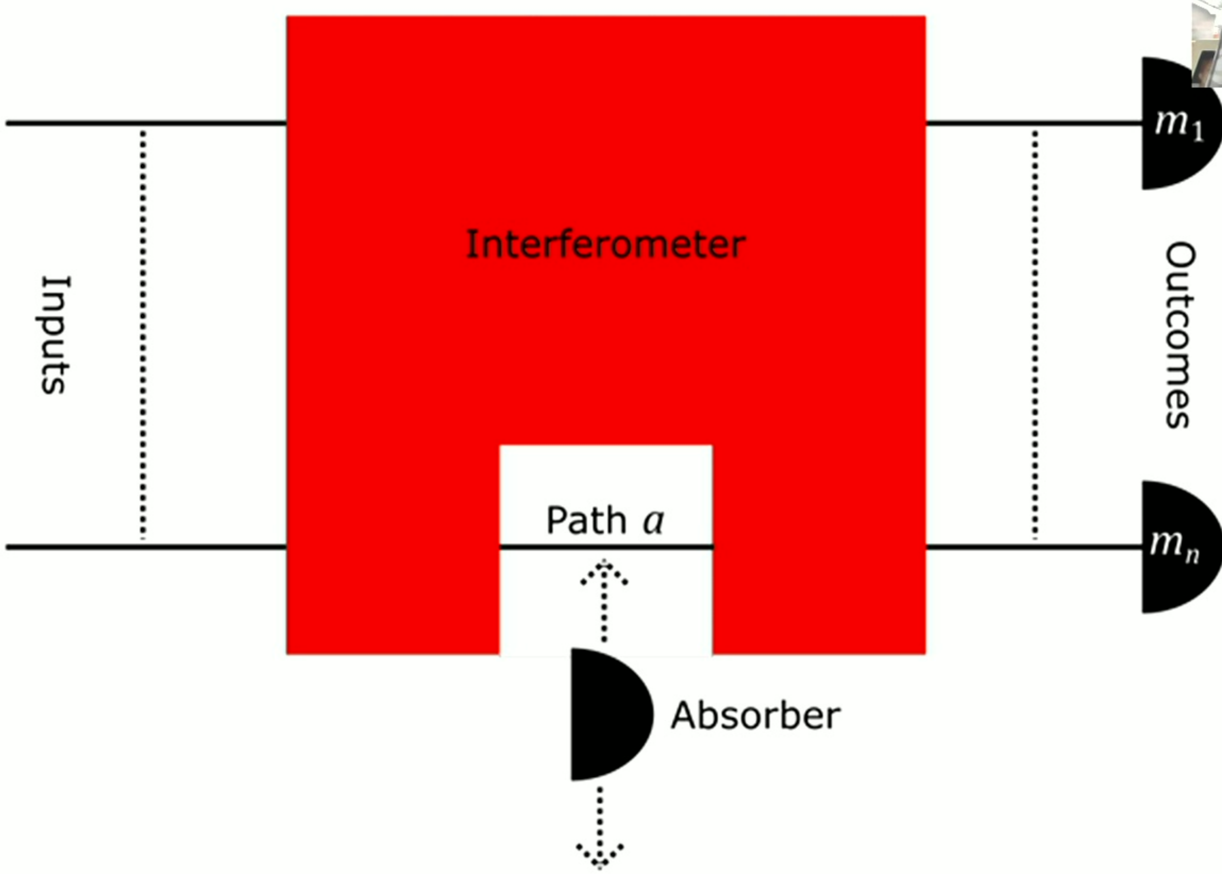
[3] Graduate School of Advanced Science and Engineering, Hiroshima University, Kagamiyama 1-3-1, Higashi Hiroshima 739-8530, Japan

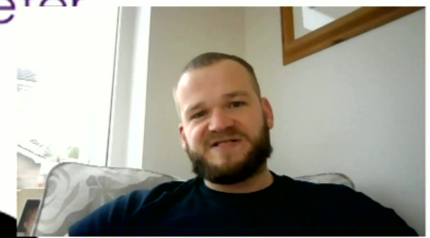
Newcastle University

HIROSHIMA UNIVERSITY

University of BRISTOL

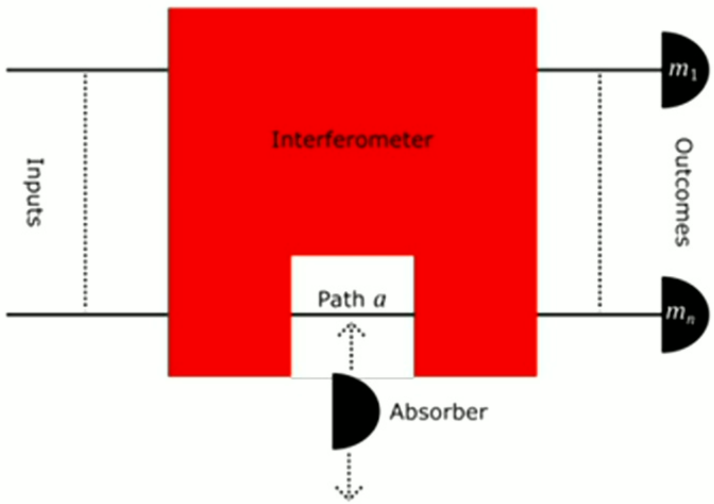
Generalised Multi-Path Single-Particle Interferometer

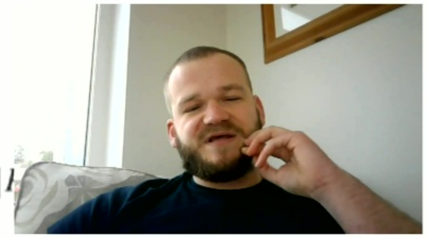




2

Statistical Distance and Counterfactual Gain





Statistical Distance: $\Delta_a \equiv \frac{1}{2}P(a) + \frac{1}{2}\sum_m |$

Classically, is always $P(a)$

Counterfactual Gain – difference between a scenario and classical Stat Distance: $\Delta_a - P(a) = \sum_{P(m|X_a)>P(m)} (P(m|X_a) - P(m))$

$$= \sum_{P(m|X_a)>P(m)} \left(|\langle m|a\rangle|^2 P(a) - 2\varrho(a,m)\right)$$

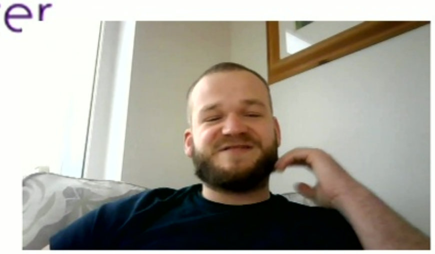
where $\varrho(a,m) = \mathrm{Re}[\langle m|a\rangle\langle a|\hat{\rho}|m\rangle]$

In EV-type Scenarios, $\varrho(a,m) = 0$
so $\Delta_a - P(a) = \sum_{P(m|X_a)>P(m)} \left(|\langle m|a\rangle|^2 P(a)\right)$

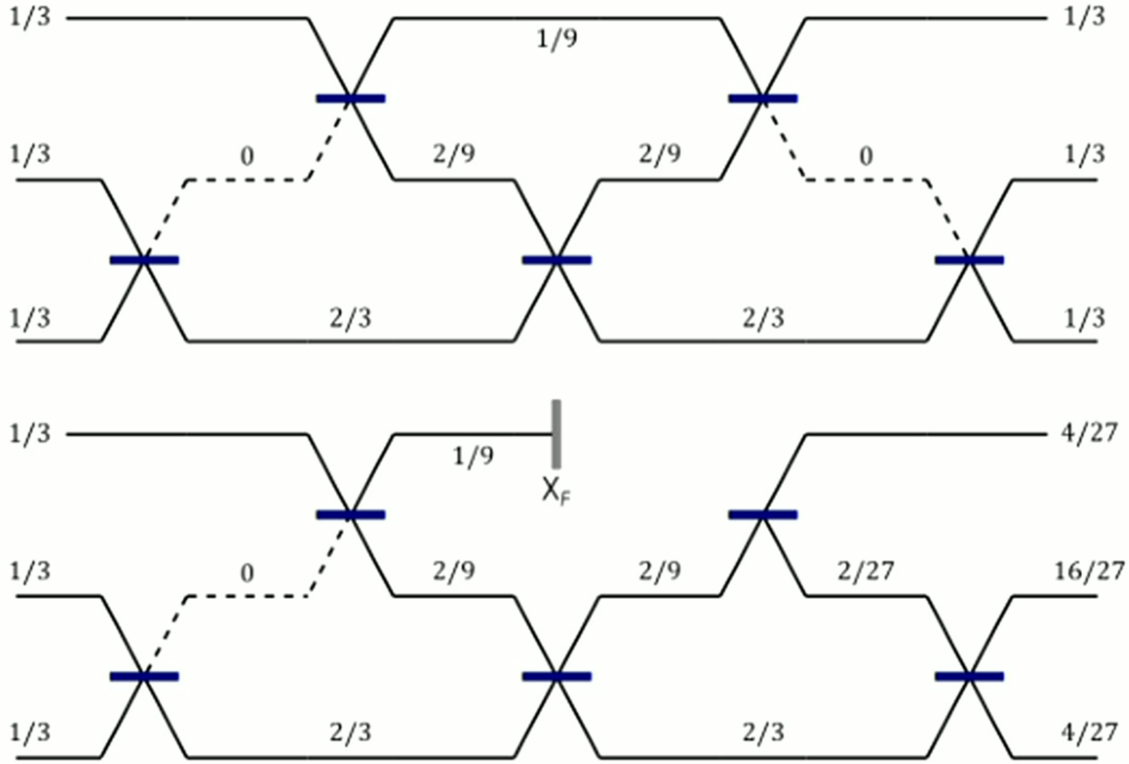
But, if $\varrho(a,m) < 0$
then the Counterfactual Gain is higher than in the EV Scenario – which hasn't been explored before!

3

Applied to Hofmann's Three-Path Interferometer



$$|N_F\rangle = \frac{1}{\sqrt{3}}\left(|1\rangle + |2\rangle + |3\rangle\right)$$



4

Wigner and friends, a map is not the territory! Contextuality in multi-agent paradoxes

arxiv.org/abs/2305.07792

Sidiney B. Montanhano

MFQ

UNICAMP

FoQaCia Conference

May 2024

Multi-agent scenarios

- Set of agents I.
- Multi-modal logic (System **S4** and topological semantics).
- Knowledge operators (K_i, E_U, D_U).
- Trust relation: i trusts j

$$(j \rightsquigarrow i) \leftrightarrow (K_i K_j \phi \to K_i \phi) \forall \phi$$

- Example: Wigner's friend scenario, Frauchiger-Renner scenario...

1

Sheaf approach to contextu

- Set X of measurements.
- Cover of contexts on X.
- Measurement scenario: sheaf of events $\mathcal{E} : \langle X, \mathcal{M} \rangle^{op} \to \mathbf{Set} :: U \mapsto O^U$.
- Empirical model: presheaf $\mathcal{D} : \mathbf{Set} \to \mathbf{Set} :: O^U \mapsto \left\{ \mu^{O^U} \right\}$.
- No-disturbance condition: $\mu^{O^j}|_{kj} = \mu^{O^k}|_{kj}$.
- Noncontextual if there is a global distribution μ^{O^X} which marginalizes to μ^{O^U}.

3

Results

Fundamental truth from trust

The following statements are valid:

- Axiom Truth turns trust relations vacuous.
- The trust relation $\overset{D}{\rightsquigarrow}$, along with the condition that $(\phi \rightarrow D_I\phi)\forall\phi$, induces a fundamental truth.

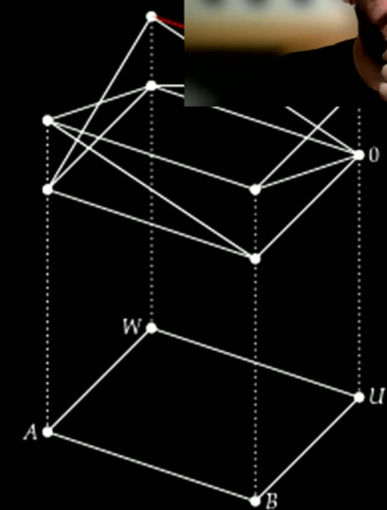
Measurement scenario as a multi-agent scenario

Measurement scenario	Multi-agent scenario
X	I
$\mathcal{U}$	$G \subset I$ with $\overset{E}{\rightsquigarrow}$ an equivalence relation
$\mathcal{E}(X)$	$\mathcal{B}_{E_I}$
$\mathcal{E}(U)_{U\in\mathcal{U}}$	$\mathcal{B}_{D_I}$

Multi-agent paradox is contextuality

Frauchiger-Renner scenario is mapped as an empirical model presenting logic contextuality.

Frauchiger-Renne



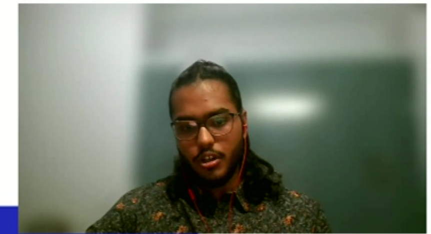
	00	01	10	11
$A \wedge B$	1/3	0	1/3	1/3
$A \wedge W$	1/6	1/6	2/3	0
$U \wedge W$	3/4	1/12	1/12	1/12
$U \wedge B$	2/3	1/6	0	1/6

Take-Home Message

- Alfred Korzybski's statement, "a map is not the territory" and ontological assumptions made in physical theories.
- Modal logic is adequate in quantum and other non-classical settings (at the cost of lambda-dependence).
- Paradoxes and contextuality are the same phenomenon (up to limitations of the Sheaf approach).

Thank you!

Sidiney B. Montanhano. **Wigner and friends, a map is not the territory! Contextuality in multi-agent paradoxes**. arXiv:2305.07792 [quant-ph].



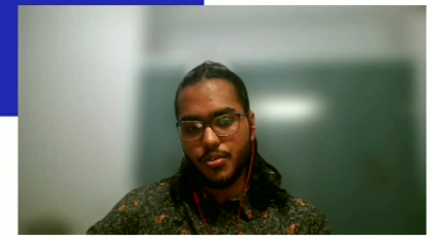
New Qutrit Tri-orthogonal Codes

Shiroman Prakash, Tanay Saha

Dayalbagh Educational Institute
Department of Physics and Computer Science

April 22, 2024

What is the optimum dimensionality of a qudit for fault-tolerance?

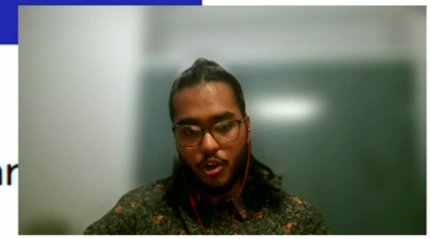


- No reason to assume qubits have best overheads/thresholds
- Hints that higher dimensions offer advantages: Classical Reed-Solomon codes/Connections to contextuality for odd prime dimensional qudits
- Experimental realizations of qutrits, Eg: (Goss et al., 2022), (Luo et al., 2023), (Subramanian & Lupascu, 2023)
- Magic state distillation: Number of noisy magic states required to produce a pure magic state scales with target noise rate ϵ as:

  $$\mathcal{O}(\log^{\gamma}(1/\epsilon)).$$

  The yield parameter γ can be compared across different dimensions
- Better yields for larger dimensions: (Krishna & Tillich, 2019), (Campbell et al., 2012). However, these constructions require large dimension ~ 17 for improvements over qubits.
- **Can we obtain better yield parameters using qutrits rather than qubits?**

Tri-orthogonal Codes



Tri-orthogonal codes are CSS codes designed to have a transversal non-Clifford gate (diagonal gate from 3rd level of the Clifford Hierar for low-overhead magic state distillation.

- Constructed from classical tri-orthogonal spaces: Linear subspace $C \subseteq \mathbb{F}^N$ s.t. $\forall\, x, y, z \in C$, $\sum_i x_i y_i z_i = 0$ and $\sum_i x_i y_i = 0$ (in $\mathbb{F}$)

Our construction:

- New family of ternary tri-orthogonal $[9m, 3m]_3$ spaces spanned by the rows of:

$$H = \begin{pmatrix} 0 & 1 & 2 & 0 & 1 & 2 & 0 & 1 & 2 & \dots \\ 2 & 2 & 2 & 1 & 1 & 1 & 0 & 0 & 0 & \dots \\ 2 & 2 & 2 & 0 & 0 & 0 & 1 & 1 & 1 & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix} \qquad (1)$$

- Used to construct $[[9m-k, k, 2]]_3$ quantum tri-orthogonal code ($k \leq 3m-2$)

Improving Magic State Distillation

- Our family of tri-orthogonal codes give yield parameter $\gamma = \log_d(n/k) = \log_2\left(2 + \frac{6}{3m-2}\right) \to 1$ as $m \to \infty$

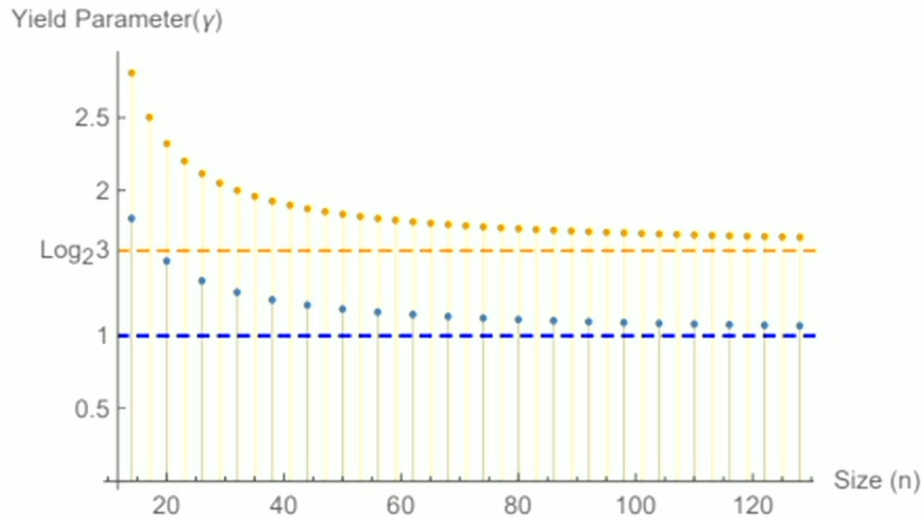


Figure: Blue-Our code; Orange-Best known qubit code (Bravyi & Haah, 2012)

- Analogous qubit construction by Brayvi & Haah has $\gamma > 1.58$
- Possible to attain $\gamma < 1$ for qubits, but we require 2^{58} qubits (Hastings & Haah, 2017)

The Hadamard Mystery
{Toffoli,Hadamard} Computationally Universal for Qua Computing

- Toffoli just represents (reversible) classical computing
- Hadamard realizes a variety of functionalities:
    - Change of basis
    - Square root of negation
    - Quantum Fourier Transform
    - Others?
- Any potential computational advantage must leverage the expressive power of Hadamard
- Two Characterizations of Hadamard-like Functionality follow
- Each provide a new perspective on Computationally Universal Quantum Computing

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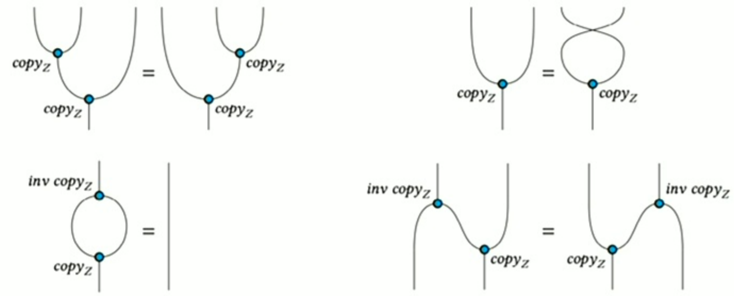
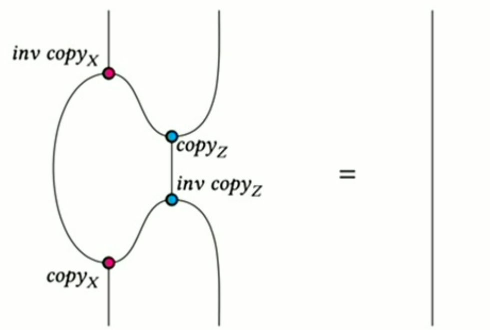
Hadamard from Two Classical Languag[e]s glued by Complementarity arXiv:2302.01885



Finding the Right Basis => Speedup ?

$FALSE_Z, TRUE_Z,$
$NOT_Z, CNOT_Z, TOFFOLI_Z,$
$COPY_Z, INV\ COPY_Z,$
...



$FALSE_X, TRUE_X,$
$NOT_X, CNOT_X, TOFFOLI_X,$
$COPY_X, INV\ COPY_X,$
...

Hadamard from Classical Language wit
Steps, 1/4 Steps, and 1/8 Steps arXiv:2310.14

Conventional classical execution

Running at Multiple Speeds => Speedup ?

Allow ½ steps with arbitrary interleaving => Quantum

Formally

Definition of the Quantum Model. The model consists of a rig groupoid $(\mathbf{C}, \otimes, \oplus, O, I)$ equipped with maps $\omega : I \to I$ and $\mathsf{V} : I \oplus I \to I \oplus I$ satisfying the equations:

$$\text{(E1)}\ \omega^8 = \text{id} \qquad \text{(E2)}\ \mathsf{V}^2 = \sigma_\oplus \qquad \text{(E3)}\ \mathsf{V} \circ \mathsf{S} \circ \mathsf{V} = \omega^2 \bullet \mathsf{S} \circ \mathsf{V} \circ \mathsf{S}$$

where $\circ$ is sequential composition, $\bullet$ is scalar multiplication (cf. Def. 4), $\sigma_\oplus$ is the symmetry on $I \oplus I$, exponents are iterated sequential compositions, and $\mathsf{S} : I \oplus I \to I \oplus I$ is defined as $\mathsf{S} = \text{id} \oplus \omega^2$.