Quantum correlations and non-Gaussian operations

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Quantum light allows us to...

Perform calculations that no classical computer can do (perhaps one day at least)

Quantum Computers Approach Milestone for Boson Sampling

December 18, 2019 • Physics 12, s146

Experiments show that when enough photons travel through a complex optical network, only a quantum computer can efficiently sample the range of possible outcomes.

Quantum computational advantage using photons

Han-Sen Zhong, Hui Wang, Yu-Hao Deng, Ming-Cheng Chen, Li-Chao Peng, Yi-Han Luo

Science 18 Dec 2020; Vol. 370, Issue 6523, pp. 1460-1463
DOI: 10.1126/science.abe8770

Quantum computational advantage with a programmable photonic processor


Nature 606, 75–81 (2022) | Cite this article
A typical photonic sampling setup

Input states are produced by a source

Quantum operations are performed

The different modes are measured

We try to find cases where it is hard for a classical computer to simulate these measurements
Quantum computational advantage

Non-Gaussianity is needed

First part of the talk

Wigner negativity is needed

High stellar rank and non-Gaussian entanglement are needed

Second part of the talk

Efficient Classical Simulation of Continuous Variable Quantum Information Processes

Stephen D. Bartlett and Barry C. Sanders
Department of Physics and Centre for Advanced Computing–Algorithms and Cryptography, Macquarie University, Sydney, New South Wales 2109, Australia
Samuel L. Braunstein and Kae Nemoto

Positive Wigner Functions Render Classical Simulation of Quantum Computation Efficient

A. Mari¹,²,³ and J. Eisert¹

Resources for Bosonic Quantum Computational Advantage

Ulysse Chabaud¹,²,⁎ and Mattia Walschaers³,†
Overview

• Non-Gaussian states from quantum correlations
• Quantum correlations from non-Gaussian operations
Overview

- Non-Gaussian states from quantum correlations
- Quantum correlations from non-Gaussian operations
How do we make non-Gaussian states?
Photon-subtraction

How the experimentalists see it

How theorists see it

The making of non-Gaussian states

Bob performs some measurement $\hat{B} = b$

$\text{Prob} [\hat{B} = b] = \langle \hat{P}_b \rangle$

We derive a quantum version of Bayes’ theorem:

$W_{A|\hat{P}_b} (\vec{x}_A) = \frac{P(\hat{B} = b | \vec{x}_A)}{\langle \hat{P}_b \rangle} W_A(\vec{x}_A)$

"Quantum conditional probability"

Can be negative!

Quantum 7, 1038 (2023).
Bob performs some measurement $\hat{B} = b$

What is quantum conditional probability?

$$P(\hat{B} = b | \vec{x}_A) = (4\pi)^{m_B} \int_{\mathbb{R}^{2m_B}} d\vec{x}_B W_{\hat{P}_b}(\vec{x}_B) W(\vec{x}_B | \vec{x}_A)$$

When can it be negative?

$$W_{A|\hat{B}_b}(\vec{x}_A) = \frac{P(\hat{B} = b | \vec{x}_A)}{\langle \hat{P}_b \rangle} W_A(\vec{x}_A)$$
Joint measurement statistics

We can express the joint probability distribution using Wigner functions

\[ P(\hat{A} = a, \hat{B} = b) = \int_{\mathbb{R}^{2m}} (4\pi)^m W_{\hat{A}=a}(\vec{x}_A) P(\hat{B} = b|\vec{x}_A) W_{\hat{\rho}_A}(\vec{x}_A) d\vec{x}_A \]

In the case of Wigner-positive measurements

\[ P(\hat{A} = a|\vec{x}_A) \]

“No Wigner negativity”

“Quantum conditional probability”
We can express the joint probability distribution using Wigner functions:

\[ P(\hat{A} = a, \hat{B} = b) = \int_{\mathbb{R}^{2m}} P(\hat{A} = a | \vec{x}_A) P(\hat{B} = b | \vec{x}_A) P(\vec{x}_A) d\vec{x}_A \]

If the quantum conditional probability is positive, this describes a local hidden variable model.

If Alice can “steer” Bob with Wigner-positive measurements, such hidden variable model cannot exist.

\[ P(\hat{B} = b | \vec{x}_A) < 0 \]
What did we learn?

When can Bob’s measurement create Wigner negativity in Alice’s subsystem?

Alice and Bob share a Gaussian state

Negativity can be created if and only if Alice can steer Bob with Gaussian measurements

PRX Quantum 1, 020305 (2020)

General case

Negativity can be created if and only if Alice can steer Bob with Wigner-positive measurements

Quantum 7, 1038 (2023).
Overview

• Non-Gaussian states from quantum correlations

• Quantum correlations from non-Gaussian operations
Entanglement and photon subtraction

**Photons subtraction** can create states where the entanglement cannot be undone by a beam splitter.

How do we measure non-Gaussian entanglement for *mixed states* in a quantum optics experiment?

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K. Zhang, J. Jing, N. Treps, MW, Quantum 6, 704 (2022).

Non-Gaussian entanglement

How can we detect non-Gaussian entanglement experimentally?

Quantum-state tomography

Ourjoumtsev, et al.

Metrological witnesses

D. Barral, et al., arXiv 2301.03909v1 (2023)

Machine learning methods?

See Mathieu's flash talk!

Xiaoting Gao

Mathieu Isoard
A state is **passively separable** if there is a passive linear optics circuit that destroys all its entanglement.

$$\hat{\rho} \overset{\bigcirc}{\longrightarrow} \sum_{\lambda} p_{\lambda} \hat{\rho}_1^{(\lambda)} \otimes \cdots \otimes \hat{\rho}_m^{(\lambda)}$$

In some sense we need states that are **not passively separable** to get a quantum computational advantage. [U. Chabaud and MW, PRL 130, 090602 (2023)]

How can we check whether a state is **passively separable**? See flash talk by Carlos!
Quantum steering is a succinct resource for measurement-based creation of Wigner negativity.

Non-Gaussian entanglement

Homodyne data contain signature of non-Gaussian entanglement. These signatures can amplified and detected by neural networks.
Outlook

Wigner negativity

Non-Gaussian entanglement
U. Chabaud, MW Phys. Rev. Lett. 130, 090602 (2023)

Quantum steering
MW Quantum 7, 1038 (2023)

Contextuality

Stellar rank
U. Chabaud, MW Phys. Rev. Lett. 130, 090602 (2023)

How is it all connected?