PRL **114,** 110504 (2015) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2015

Entanglement-Based Machine Learning on a Quantum Computer

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(Received 16 November 2014; published 19 March 2015)

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NOV 18, 2016

Outline

- Motivation: Interplay of machine learning and quantum information
- Background: Tasks in machine learning
- Principle: Using entangled photons to obtain essential information from data
- Significance: First realization, new possibilities, and potential applications for manipulation of high dimensional vectors (big data)
- Experimental setup
- Measurements and results
- Conclusions & critique

Quantum Machine Learning offers speedup over classical algorithms

1. Machine Learning (ML): algorithms that learn from and make predictions on data

2. Quantum Information (QI): qubits exhibit potential of encoding large information in Hilbert space

3. The combination of ML and QI leads to potential manipulation of large data using fewer steps and resources

Machine learning involves certain fundamental tasks

1. Supervised machine learning

2. Unsupervised machine learning

3. Fundamental task: evaluation of the distance and inner products between high-dimensional vectors to analyze the similarity between vectors

The algorithm for using entangled photons to determine inner products

To compute the inner product of $|u\rangle$ and $|v\rangle$ adjoin these states with an ancillary qubit

$$|\varphi\rangle = (|0\rangle_{\mathrm{anc}}|u\rangle_{\mathrm{new}} + |1\rangle_{\mathrm{anc}}|v\rangle_{\mathrm{ref}})/\sqrt{2}.$$

A single-qubit projective measurement is placed on the ancillary qubit to see if it is on the state:

$$|\phi\rangle = (|u||0\rangle - |v||1\rangle)/\sqrt{|u|^2 + |v|^2}.$$

The inner product and the "distance" D of two vectors are given by the success probability p of the projective measurement

$$\langle u|v\rangle == (0.5 - p)(|u|^2 + |v|^2)/|u||v| \qquad D = \sqrt{2p(|u|^2 + |v|^2)}$$

Principle, using entangled photons to obtain essential information of data

Significance of the work

1. First experimental demonstration of machine learning on a photonic quantum computer

2. The inner product is measured through the success probability p, which is not related to the dimension of the vector

3. Method provides a way to obtain essential information of high-dimensional vector using fewer steps and resources

Experimental Setup

For more details, please contact:
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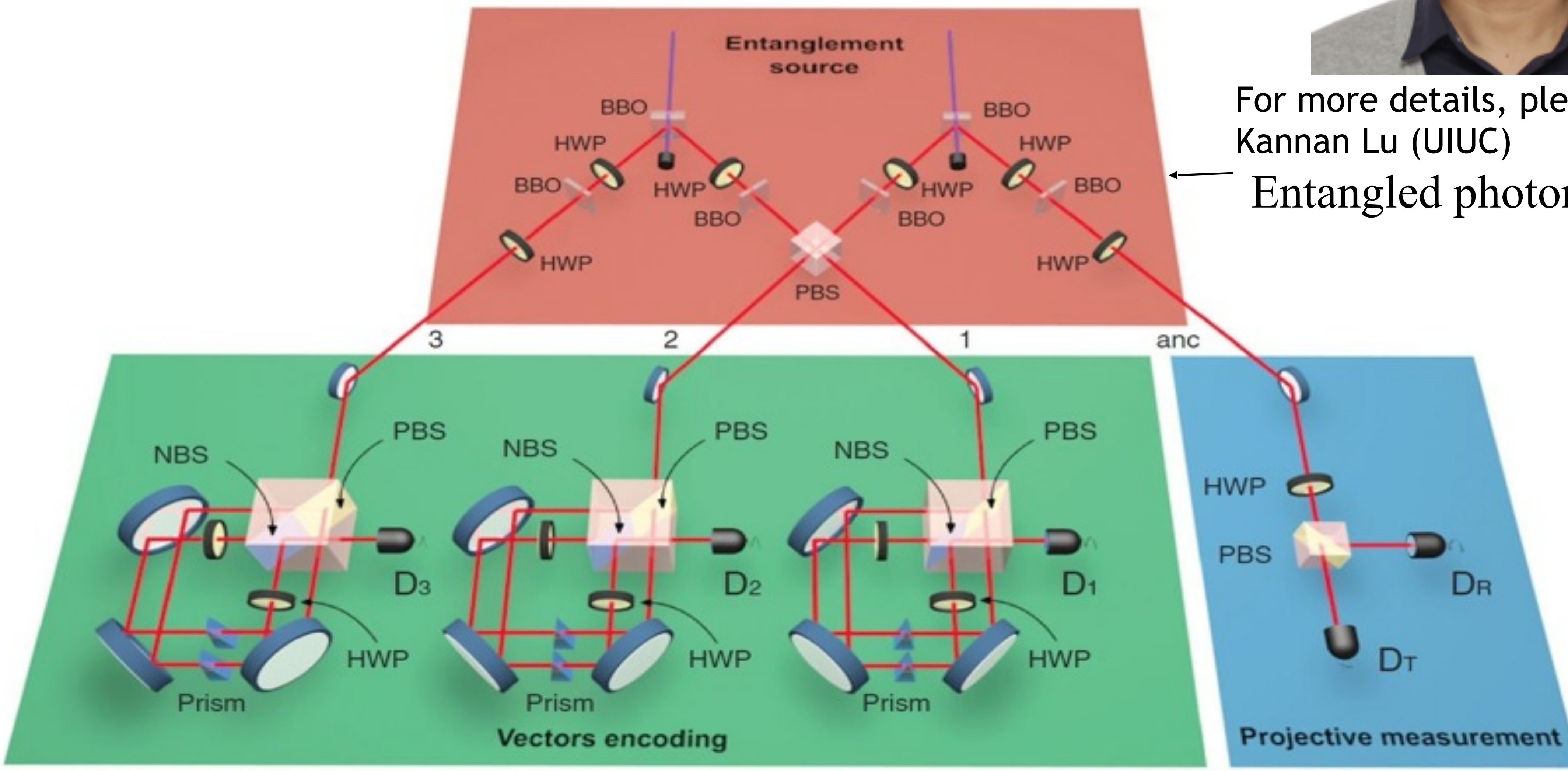


Entangled photon generator

Adjoin with ancillary photon

Measurement of ancillary photon

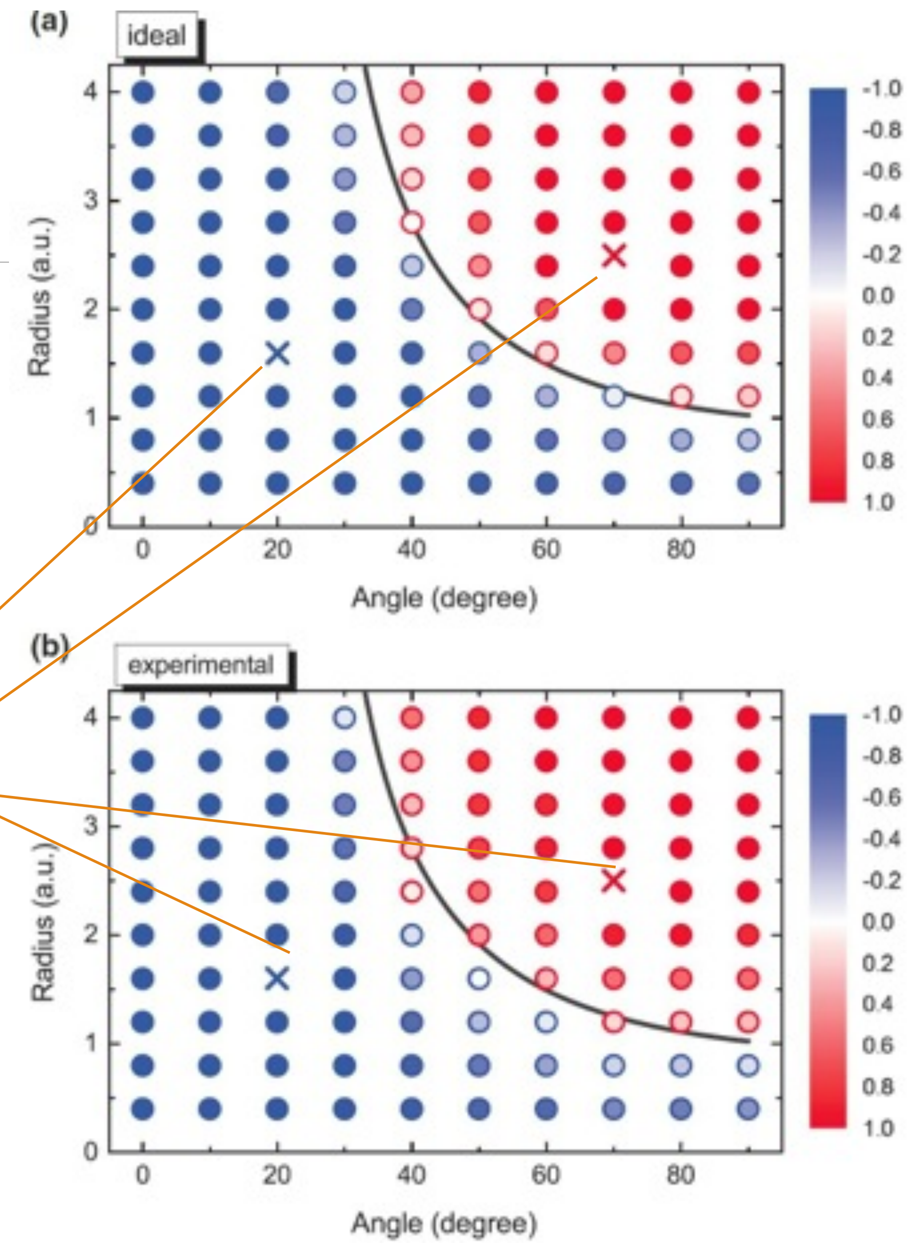
Entanglement fidelity for two-, three-, four-photon entangled states are 0.94, 0.73 and 0.75

Test of the entanglement algorithm

Given two reference vectors, A and B
Given many other vectors to classify by distance
Classification criterion:

$$D_A - D_B \begin{cases} <0 \text{ red cluster} \\ >0 \text{ blue cluster} \end{cases}$$

Reference vector



Test of the entanglement algorithm

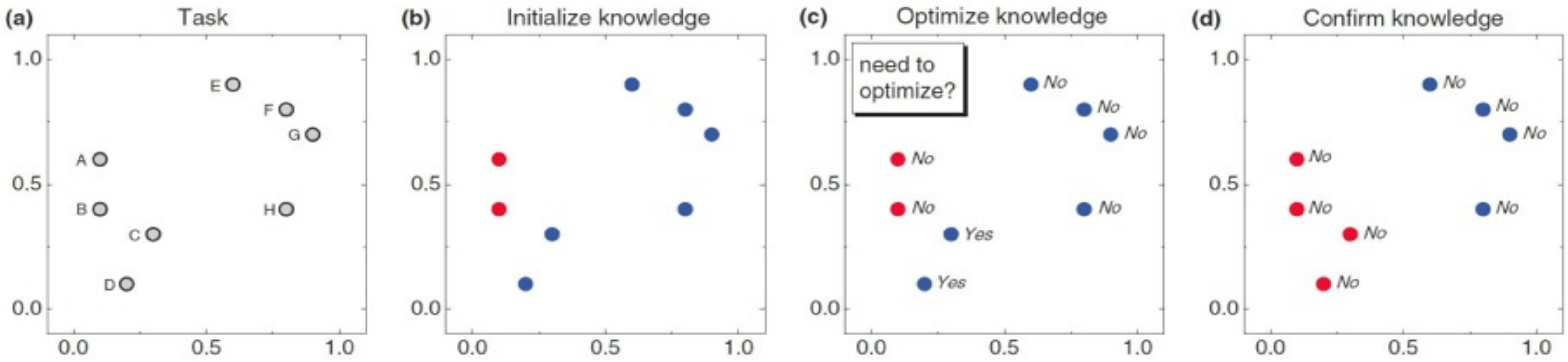
- Test on Eight Dimensional Vector

Test vectors		$\frac{D_A - D_B}{\text{Theory Exp.}}$		Group	Correct?
1	(2.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00)	−1.24	−0.84	*A*	✓
2	(0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.60)	0.77	0.55	*B*	✓
3	(1.77, 0.00, 0.00, 0.00, 1.24, 0.00, 0.00, 0.00)	−0.92	−0.52	*A*	✓
4	(0.40, 0.23, 0.11, 0.06, 0.03, 0.02, 0.01, 0.01)	−0.45	−0.14	*A*	✓
5	(0.00, 0.00, 1.23, 1.23, 0.00, 0.00, 0.33, 0.33)	0.17	0.10	*B*	✓
6	(0.30, 0.03, 0.30, 0.03, 1.12, 0.10, 1.12, 0.10)	−0.11	−0.24	*A*	✓
7	(0.42, 0.90, 0.35, 0.76, 0.00, 0.00, 0.00, 0.00)	−0.28	−0.21	*A*	✓
8	(0.54, 0.54, 0.00, 0.00, 0.54, 0.54, 0.00, 0.00)	−0.43	−0.50	*A*	✓
9	(0.11, 1.24, 0.19, 2.15, 0.06, 0.72, 0.11, 1.24)	0.40	−0.17	*A*	×

First demonstration of unsupervised machine learning with entangled photons

- Further application on unsupervised learning

Goal: To classify different data points without reference vectors



Conclusions

1. A algorithm for calculating inner product has been implemented on a quantum computer using entangled photons. It has important applications to both supervised and unsupervised learning problems.

2. The complexity of the algorithm on a quantum computer is $O(\log(N))$ for the evaluation. It is much faster than the same algorithm on the classical computer.

3. This work demonstrates the possibility of using machine learning for high dimension vectors.

Critiques

1. Inaccurate expressions for certain formulas.

2. Though the work shows a possible faster approach for obtaining inner product and distance by using quantum entanglement, the fidelity of entanglement still affects.For low fidelity, the result may be inaccurate since fewer photons get entangled.

3. In this experiment, only have four photons entangled, which can handle 8 dimensional vector. For application, more entangled photons are required.