REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
26-07-2022	Final Report	29-Sep-2017 - 31-Mar-2022

4. TITLE AND SUBTITLE	
Final Report: Quantum Machine Learning	5a. CONTRACT NUMBER W911NF-17-1-0527
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 106011
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Massachusetts Institute of Technology (MIT 77 Massachusetts Avenue NE18-901 Cambridge, MA 02139 -4307	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 71934-PH.49

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Seth Lloyd
UU	UU	UU	UU		19b. TELEPHONE NUMBER 617-252-1803

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 04-Aug-2022

Agency Code: 21XD

Proposal Number: 71934PH **Agreement Number: W911NF-17-1-0527**

INVESTIGATOR(S):

Name: Seth Lloyd
Email: slloyd@mit.edu
Phone Number: 6172521803
Principal: Y

Organization: **Massachusetts Institute of Technology (MIT)**
Address: 77 Massachusetts Avenue, Cambridge, MA 021394307
Country: USA
DUNS Number: 001425594 EIN: 042103594

Report Date: 30-Jun-2022 Date Received: 26-Jul-2022
Final Report for Period Beginning 29-Sep-2017 and Ending 31-Mar-2022
Title: Quantum Machine Learning
Begin Performance Period: 29-Sep-2017 **End Performance Period:** 31-Mar-2022
Report Term: 0-Other
Submitted By: Seth Lloyd Email: slloyd@mit.edu
Phone: (617) 252-1803
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 6 **STEM Participants:** 10

Major Goals: Major Goals: As stated in the proposal, the major goals of the program were as follows:

Develop quantum algorithms for topological and geometric analysis of data that can supply exponential speed ups over classical methods, even in the absence of qRAM.

Develop a set of quantum Basic Linear Algebra Subroutines (qBLAS): these will provide the work horses for constructing quantum machine learning algorithms that provide exponential speed up for classical devices when qRAM is available.

Work with experimentalists to design and realize large-scale qRAM.

Develop quantum machine learning techniques for the analysis of quantum data that are exponentially more efficient than semi-classical methods for data analysis and tomography.

Develop a theory of universal deep quantum learning, and of deep quantum learning on tunable integrated photonic circuits.

Accomplishments: We accomplished all of our major goals for this program.

Principle activities and findings:
The research supported by this grant focused on problems of quantum machine learning: how do you load data onto a quantum computer, and process it to reveal patterns that classical computers can't find? When the grant commenced, in 2017, the field of quantum machine learning was in its infancy. There were a few results on quantum algorithms for clustering, principal component analysis, and topological analysis of data, as well as designs for quantum random access memory (qRAM): but quantum machine learning had yet to emerge as an established discipline of scientific study.

In the intervening five years, the field of quantum machine learning has expanded dramatically. The work supported by this grant played a key role in several branches of quantum machine learning. (See our review paper, reference [1], for a general description of the field. This work, one of the first works supported by the grant, has become the central reference and the most highly cited paper in the field of quantum machine learning.)

(1) Quantum generative adversarial networks (qGAN):

We established the paradigm of quantum generative adversarial networks (qGAN), in which a quantum generator tries to generate data that can deceive a quantum discriminator [26]. We proved the convergence of such networks to optimal solutions, and showed how quantum generative networks can substantially out-perform classical generative networks.

(2) Quantum neural networks:
Prior to 2017, there was no accepted general definition for the quantum neural networks. We established the now-accepted design and framework for continuous variable quantum neural networks [20,40]. We provided the first design for quantum recurrent neural networks [12]. We showed how a quantum Hopfield network can provide exponential advantages over classical Hopfield networks [24]. We developed a quantum algorithm for simulating the neural tangent kernel and for training large neural networks [62].

(3) Quantum differential equation solvers:
Because of their ability to represent 2n dimensional vectors as the state of n qubits, quantum computers have the potential for solving differential equations exponentially more efficiently than classical computers. We provided the first formulation for solving continuous variable differential equations by showing how to invert infinite-dimensional operators [23,39]. We showed how quantum computers can reveal non-trivial features of the solutions of differential equations by performing quantum post-processing [53,68].

Finally, we showed how quantum computers can be used to solve nonlinear differential equations by using interactions between multiple copies of the system [54], in analogue to the use of non-linear Schr ̈odinger equations to describe the behavior of Bose-Einstein condensates.

(4) Quantum algorithms for machine learning
Over the course of the program, we developed a number of novel quantum algorithms focused on machine learning and data analysis. We developed efficient quantum algorithms for spectral estimation [2], for Gaussian hypothesis testing [14], for quantum- singular value decomposition [15], for portfolio optimization [27], for gradient descent and Newton's method [38], for medical imaging [48], for performing the matrix polar decomposition [50], and for pretty good measurements and channel decoding [51,71].

We developed quantum algorithms for group convolution, cross correlation, and equivariant transformations [65] – i.e., for the central algebraic methods underlying the analysis of data with symmetries.

We established the basic methods for quantum kernel analysis, in which classical data is embedded as quantum states in a high-dimensional Hilbert space, and optimal quantum measurements are then performed to discriminate between clusters of data [46].

We showed how problems of barren plateaus in variational quantum algorithms can be avoided by using a quantum version of Earth-Mover's (Wasserstein 1) distance [55,60].

(5) Quantum inspired algorithms
The potential for quantum inspired algorithms was first pointed out by Ewin Tang in 2018, who noted that the quantum principal component analysis algorithm for low-rank matrices could be simulated classically using existing low-rank matrix techniques. Together with Andras Gilyen, we showed how quantum inspired techniques could be extended to matrix inversion and the quantum singular value transform for low rank matrices [28], and we performed detailed simulations of how such quantum inspired algorithms would play out when applied to very large classical data sets [37].

(6) Classical deep learning
We applied methods from quantum computing to derive several results in the field of classical deep learning. First, we showed that classical deep neural networks are biased towards functions that are simple and robust [30,45]. Next, in collaboration with Yann Lecun, we showed how the linear transformations of deep neural networks can be replaced with unitary transformations, with attendant improvements on performance and convergence [73].

7. Quantum sensing and control
We developed applications of quantum sensing and control to quantum machine learning, with the goal of finding and taking advantage of patterns in the behavior of quantum systems. We investigated geometric methods of quantum control [4], methods for the quantum control of graphical systems [13], photonic quantum sensing [29], entanglement enhanced sensing via post-selection [34,52], and non-Markovian effects in quantum measurement [74].

8. Experimental collaborations
During the course of the grant, we developed experimental applications of the fun- damental ideas developed by the theoretical efforts. In particular, our ideas on quantum walks and quantum transport on complex graphs were realized experimentally in the context of photonics by Dirk Englund's group [10,11], and in the context of excitonic transport by Moungi Bawendi's group [18,25]. Our work on quantum principal component analysis and density matrix exponentiation was realized experimentally by Will Oliver [42,47,67]. The Englund group also realized our method for variational learning of quantum circuits [47], and we collaborated on the experimental design of qRAM [58,63].

The Englund and Oliver groups are continuing with experimental demonstrations of our work on quantum circuits, qGANs, and qRAM.

Training Opportunities: The program trained 10 graduate students and 1 undergraduate intern.

The program supported 5 postdoctoral fellows, all of whom now have faculty positions in research universities.

Results Dissemination: The primary means of dissemination of the results were published papers and talks at professional meetings.

The grant supported wholly or in part 74 publications (see list).

The results of the work were reported at numerous conferences, including the APS March meeting (yearly), IEEE quantum, NIPS, AQC, and SQUINT.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Faculty
Participant: Peter Shor
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: Y

Participant Type: Faculty
Participant: Dirk Englund
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Faculty
Participant: William Oliver
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Faculty

Participant: Stefano Pirandola
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Patrick Rebentrost
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Iman Marvian
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Giacomo De Palma
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Milad Marvian
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zi-Wen Liu
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Can Gokler
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Kevin Thompson
Person Months Worked: 12.00 **Funding Support:**

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Reevu Maity
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: David Arvidsson-Shukur
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Bobak Kiani
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Ryuji Takagi
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Oles Shtanko
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Lara Booth
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Samuel Bosch
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report
as of 04-Aug-2022

Participant Type: Graduate Student (research assistant)
Participant: Grecia Castelazo
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Quynh Nguyen
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

International Collaboration:

GBR

GBR

GBR

JPN

GBR

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.122.100401
Volume: 122 Issue: 10 First Page #:
Date Submitted: 5/24/19 12:00AM Date Published: 3/1/19 5:00AM
Publication Location:
Article Title: Entropic Energy-Time Uncertainty Relation
Authors: Patrick J. Coles, Vishal Katariya, Seth Lloyd, Iman Marvian, Mark M. Wilde
Keywords: quantum computing
Abstract: Energy-time uncertainty plays an important role in quantum foundations and technologies, and it was even discussed by the founders of quantum mechanics. However, standard approaches (e.g., Robertson's uncertainty relation) do not apply to energy-time uncertainty because, in general, there is no Hermitian operator associated with time. Following previous approaches, we quantify time uncertainty by how well one can read off the time from a quantum clock. We then use entropy to quantify the information-theoretic distinguishability of the various time states of the clock. Our main result is an entropic energy-time uncertainty relation for general time-independent Hamiltonians, stated for both the discrete-time and continuous-time cases.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.119.120501
Volume: 119 Issue: 12 First Page #:
Date Submitted: 5/24/19 12:00AM Date Published: 9/1/17 4:00AM
Publication Location: New York
Article Title: Gaussian Hypothesis Testing and Quantum Illumination
Authors: Mark M. Wilde, Marco Tomamichel, Seth Lloyd, Mario Berta
Keywords: quantum computing
Abstract: Quantum hypothesis testing is one of the most basic tasks in quantum information theory and has fundamental links with quantum communication and estimation theory. In this paper, we establish a formula that characterizes the decay rate of the minimal type-II error probability in a quantum hypothesis test of two Gaussian states given a fixed constraint on the type-I error probability. This formula is a direct function of the mean vectors and covariance matrices of the quantum Gaussian states in question. We give an application to quantum illumination, which is the task of determining whether there is a low-reflectivity object embedded in a target region with a bright thermal-noise bath. For the asymmetric-error setting, we find that a quantum illumination transmitter can achieve an error probability exponent stronger than a coherent-state transmitter of the same mean photon number, and furthermore, that it requires far fewer trials to do so.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.25.021275
Volume: 25 Issue: 18 First Page #: 21275
Date Submitted: 5/24/19 12:00AM Date Published: 8/1/17 12:00AM
Publication Location:
Article Title: Programmable dispersion on a photonic integrated circuit for classical and quantum applications
Authors: Jelena Notaros, Jacob Mower, Mikkel Heuck, Cosmo Lupo, Nicholas C. Harris, Gregory R. Steinbrecher
Keywords: quantum computing
Abstract: We demonstrate a large-scale tunable-coupling ring resonator array, suitable for high-dimensional classical and quantum transforms, in a CMOS-compatible silicon photonics platform. The device consists of a waveguide coupled to 15 ring-based dispersive elements with programmable linewidths and resonance frequencies. The ability to control both quality factor and frequency of each ring provides an unprecedented 30 degrees of freedom in dispersion control on a single spatial channel. This programmable dispersion control system has a range of applications, including mode-locked lasers, quantum key distribution, and photon-pair generation. We also propose a novel application enabled by this circuit – high-speed quantum communications using temporal-mode-based quantum data locking – and discuss the utility of the system for performing the high-dimensional unitary optical transformations necessary for a quantum data locking demonstration.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature
Publication Identifier Type: DOI Publication Identifier: 10.1038/nature23474
Volume: 549 Issue: 7671 First Page #: 195
Date Submitted: 5/24/19 12:00AM Date Published: 9/1/17 12:00AM
Publication Location:
Article Title: Quantum machine learning
Authors: Jacob Biamonte, Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Wiebe, Seth Lloyd
Keywords: quantum computing
Abstract: Fuelled by increasing computer power and algorithmic advances, machine learning techniques have become powerful tools for finding patterns in data. Quantum systems produce atypical patterns that classical systems are thought not to produce efficiently, so it is reasonable to postulate that quantum computers may outperform classical computers on machine learning tasks. The field of quantum machine learning explores how to devise and implement quantum software that could enable machine learning that is faster than that of classical computers. Recent work has produced quantum algorithms that could act as the building blocks of machine learning programs, but the hardware and software challenges are still considerable.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Photonics
Publication Identifier Type: DOI Publication Identifier: 10.1038/nphoton.2017.95
Volume: 11 Issue: 7 First Page #: 447
Date Submitted: 5/24/19 12:00AM Date Published: 6/1/17 4:00AM
Publication Location:
Article Title: Quantum transport simulations in a programmable nanophotonic processor
Authors: Nicholas C. Harris, Gregory R. Steinbrecher, Mihika Prabhu, Yoav Lahini, Jacob Mower, Darius Bunand
Keywords: quantum computing
Abstract: Environmental noise and disorder play critical roles in quantum particle and wave transport in complex media, including solid-state and biological systems. While separately both effects are known to reduce transport, recent work predicts that in a limited region of parameter space, noise-induced dephasing can counteract localization effects, leading to enhanced quantum transport. Photonic integrated circuits are promising platforms for studying such effects, with a central goal of developing large systems providing low-loss, high-fidelity control over all parameters of the transport problem. Here, we fully map the role of disorder in quantum transport using a nanophotonic processor: a mesh of 88 generalized beamsplitters programmable on microsecond timescales.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.118.260501
Volume: 118 Issue: 26 First Page #:
Date Submitted: 5/24/19 12:00AM Date Published: 6/1/17 4:00AM
Publication Location:
Article Title: Efficiently Controllable Graphs
Authors: Can Gokler, Seth Lloyd, Peter Shor, Kevin Thompson
Keywords: quantum computing
Abstract: We investigate graphs that can be disconnected into small components by removing a vanishingly small fraction of their vertices. We show that when a quantum network is described by such a graph, the network is efficiently controllable, in the sense that universal quantum computation can be performed using a control sequence polynomial in the size of the network while controlling a vanishingly small fraction of subsystems. We show that networks corresponding to finite-dimensional lattices are efficently controllable, and explore generalizations to percolation clusters and random graphs. We show that the classical computational complexity of estimating the ground state of Hamiltonians described by controllable graphs is polynomial in the number of subsystems/qubits.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: DOI Publication Identifier: 10.1088/1367-2630/aa5e48
Volume: 19 Issue: 3 First Page #: 033005
Date Submitted: 5/24/19 12:00AM Date Published: 3/1/17 12:00AM
Publication Location:
Article Title: An efficient quantum algorithm for spectral estimation
Authors: Adrian Steffens, Patrick Rebentrost, Iman Marvian, Jens Eisert, Seth Lloyd
Keywords: quantum computing
Abstract: We develop an efficient quantum implementation of an important signal processing algorithm for line spectral estimation: the matrix pencil method, which determines the frequencies and damping factors of signals consisting of finite sums of exponentially damped sinusoids. Our algorithm provides a quantum speedup in a natural regime where the sampling rate is much higher than the number of sinusoid components. Along the way, we develop techniques that are expected to be useful for other quantum algorithms as well—consecutive phase estimations to efficiently make products of asymmetric low rank matrices classically accessible and an alternative method to efficiently exponentiate non-Hermitian matrices.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Physics A: Mathematical and Theoretical
Publication Identifier Type: DOI Publication Identifier: 10.1088/1751-8121/ab0774
Volume: 52 Issue: 13 First Page #: 135301
Date Submitted: 5/24/19 12:00AM Date Published: 3/1/19 5:00AM
Publication Location:
Article Title: Diagonal quantum discord
Authors: Zi-Wen Liu, Ryuji Takagi, Seth Lloyd
Keywords: quantum computing
Abstract: Quantum discord measures quantum correlation by comparing the quantum mutual information with the maximal amount of mutual information accessible to a quantum measurement. This paper analyzes the properties of diagonal discord, a simplified version of discord that compares quantum mutual information with the mutual information revealed by a measurement that correspond to the eigenstates of the local density matrices. In contrast to the optimized discord, diagonal discord is easily computable; it also finds connections to thermodynamics and resource theory. Here we further show that, for the generic case of non-degenerate local density matrices, diagonal discord exhibits desirable properties as a preferable discord measure.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Photonics
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41566-018-0301-6
Volume: 12 Issue: 12 First Page #: 724
Date Submitted: 5/24/19 12:00AM Date Published: 11/1/18 4:00AM
Publication Location:
Article Title: Advances in photonic quantum sensing
Authors: S. Pirandola, B. R. Bardhan, T. Gehring, C. Weedbrook, S. Lloyd
Keywords: quantum computing
Abstract: Quantum sensing has become a broad field. It is generally related with the idea of using quantum resources to boost the performance of a number of practical tasks, including the radar-like detection of faint objects, the readout of information from optical memories, and the optical resolution of extremely close point-like sources. Here, we first focus on the basic tools behind quantum sensing, discussing the most recent and general formulations for the problems of quantum parameter estimation and hypothesis testing. With this basic background in hand, we then review emerging applications of quantum sensing in the photonic regime both from a theoretical and experimental point of view.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.121.040502
Volume: 121 Issue: 4 First Page #:
Date Submitted: 5/24/19 12:00AM Date Published: 7/1/18 8:00AM
Publication Location:
Article Title: Quantum Generative Adversarial Learning
Authors: Seth Lloyd, Christian Weedbrook
Keywords: quantum computing
Abstract: We develop an efficient quantum implementation of an important signal processing algorithm for line spectral estimation: the matrix pencil method, which determines the frequencies and damping factors of signals consisting of finite sums of exponentially damped sinusoids. Our algorithm provides a quantum speedup in a natural regime where the sampling rate is much higher than the number of sinusoid components. Along the way, we develop techniques that are expected to be useful for other quantum algorithms as well—consecutive phase estimations to efficiently make products of asymmetric low rank matrices classically accessible and an alternative method to efficiently exponentiate non-Hermitian matrices.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.118.060502
Volume: 118 Issue: 6 First Page #:
Date Submitted: 5/24/19 12:00AM Date Published: 2/1/17 5:00AM
Publication Location:
Article Title: Resource Destroying Maps
Authors: Zi-Wen Liu, Xueyuan Hu, Seth Lloyd
Keywords: quantum computing
Abstract: Resource theory is a widely applicable framework for analyzing the physical resources required for given tasks, such as computation, communication, and energy extraction. In this Letter, we propose a general scheme for analyzing resource theories based on resource destroying maps, which leave resource-free states unchanged but erase the resource stored in all other states. We introduce a group of general conditions that determine whether a quantum operation exhibits typical resource-free properties in relation to a given resource destroying map. Our theory reveals fundamental connections among basic elements of resource theories, in particular, free states, free operations, and resource measures.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications 11, 3775 (2020)
Publication Identifier Type: Other Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 7/29/20 6:08PM
Publication Location:
Article Title: Quantum advantage in post-selected metrlogy
Authors: David R. M. Arvidsson-Shukur, Nicole Yunger Halpern, Hugo V. Lepage, Aleksander A. Lasek, Crispin H
Keywords: Quantum information
Abstract: We show that postselection offers a nonclassical advantage in metrology. In every parameter-estimation experiment, the final measurement or the postprocessing incurs some cost. Postselection can improve the rate of Fisher information (the average information learned about an unknown parameter from an experimental trial) to cost. This improvement, we show, stems from the negativity of a quasiprobability distribution, a quantum extension of a probability distribution. In a classical theory, in which all observables commute, our quasiprobability distribution can be expressed as real and nonnegative. In a quantum-mechanically noncommuting theory, nonclassicality manifests in negative or nonreal quasiprobabilities. The distribution's nonclassically negative values enable postselected experiments to outperform even postselection-free experiments whose input states and final measurements are optimized: Postselected quantum experiments can yield anomalously large information-cost rates.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Quantum
Publication Identifier Type: DOI Publication Identifier: 10.22331/q-2020-08-13-307
Volume: 4 Issue: First Page #: 307
Date Submitted: 10/8/20 12:00AM Date Published: 8/1/20 4:00AM
Publication Location:
Article Title: Quantum-inspired algorithms in practice
Authors: Juan Miguel Arrazola, Alain Delgado, Bhaskar Roy Bardhan, Seth Lloyd
Keywords: quantum algorithms, quantum machine learning
Abstract: We show that postselection offers a nonclassical advantage in metrology. In every parameter-estimation experiment, the final measurement or the postprocessing incurs some cost. Postselection can improve the rate of Fisher information (the average information learned about an unknown parameter from an experimental trial) to cost. This improvement, we show, stems from the negativity of a quasiprobability distribution, a quantum extension of a probability distribution. In a classical theory, in which all observables commute, our quasiprobability distribution can be expressed as real and nonnegative. In a quantum-mechanically noncommuting theory, nonclassicality manifests in negative or nonreal quasiprobabilities. The distribution's nonclassically negative values enable postselected experiments to outperform even postselection-free experiments whose input states and final measurements are optimized: Postselected quantum experiments can yield anomalously large information-cost rates.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 8/30/19 6:19PM
Publication Location:
Article Title: Emergent Prethermalization Signatures in Out-of-Time Ordered Correlations
Authors: Ken Xuan Wei, Pai Peng, Oles Shtanko, Iman Marvian, Seth Lloyd, Chandrasekhar Ramanathan, Paola
Keywords: Quantum simulation
Abstract: How a many-body quantum system thermalizes—or fails to do so—under its own interaction is a fundamental yet elusive concept. Here we demonstrate nuclear magnetic resonance observation of the emergence of prethermalization by measuring out-of-time ordered correlations. We exploit Hamiltonian engineering techniques to tune the strength of spin-spin interactions and of a transverse magnetic field in a spin chain system, as well as to invert the Hamiltonian sign to reveal out-of-time ordered correlations. At large fields, we observe an emergent conserved quantity due to prethermalization, which can be revealed by an early saturation of correlations. Our experiment not only demonstrates a new protocol to measure out-of- time ordered correlations, but also provides new insights in the study of quantum thermodynamics.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Physics
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 1/13/20 7:23PM
Publication Location:
Article Title: Variational quantum unsampling on a quantum photonic processor
Authors: Jacques Carolan, Masoud Mohseni, Jonathan P. Olson, Mihika Prabhu, Changchen Chen, Darius Buna
Keywords: Quantum computation
Abstract: A promising route towards the demonstration of near-term quantum advantage (or supremacy) over classical systems relies on running tailored quantum algorithms on noisy intermediate-scale quantum machines. These algorithms typically involve sampling from probability distributions that—under plausible complexity-theoretic conjectures—cannot be efficiently generated classically. Rather than determining the computational features of output states produced by a given physical system, we investigate what features of the generating system can be efficiently learnt given direct access to an output state. To tackle this question, here we introduce the variational quantum unsampling protocol, a nonlinear quantum neural network approach for verification and inference of near-term quantum circuit outputs. In our approach, one can variationally train a quantum operation to unravel the action of an unknown unitary on a known input state, essentially learning the inverse of the quantum dynamics.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Phys. Rev. Research
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 10/31/19 6:27PM
Publication Location:
Article Title: Continuous-variable quantum neural network
Authors: Nathan Killoran, Thomas R. Bromley, Juan Miguel Arrazola, Maria Schuld, Nicolás Quesada, Seth Lloyc
Keywords: quantum machine learning
Abstract: We introduce a general method for building neural networks on quantum computers. The quantum neural network is a variational quantum circuit built in the continuous-variable (CV) architecture, which encodes quantum information in continuous degrees of freedom such as the amplitudes of the electromagnetic field. This circuit contains a layered structure of continuously parameterized gates which is universal for CV quantum computation. Affine transformations and nonlinear activation functions, two key elements in neural networks, are enacted in the quantum network using Gaussian and non-Gaussian gates, respectively. The non-Gaussian gates provide both the nonlinearity and the universality of the model. Due to the structure of the CV model, the CV quantum neural network can encode highly nonlinear transformations while remaining completely unitary. We show how a classical network can be embedded into the quantum formalism and propose quantum versions of various specialized models.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 9/4/19 6:31PM
Publication Location:
Article Title: Quantum algorithm for nonhomogeneous linear partial differential equations
Authors: Juan Miguel Arrazola, Timjan Kalajdzievski, Christian Weedbrook, Seth Lloyd
Keywords: quantum machine learning
Abstract: We describe a quantum algorithm for preparing states that encode solutions of nonhomogeneous linear partial differential equations. The algorithm is a continuous-variable version of matrix inversion: it efficiently inverts differential operators that are polynomials in the variables and their partial derivatives. The output is a quantum state whose wave function is proportional to a specific solution of the nonhomogeneous differential equation, which can be measured to reveal features of the solution. The algorithm consists of three stages: preparing fixed resource states in ancillary systems, performing Hamiltonian simulation, and measuring the ancilla systems. The algorithm can be carried out using standard methods for gate decompositions, but we improve this in two ways. First, we show that for a wide class of differential operators, it is possible to derive exact decompositions for the gates employed in Hamiltonian simulation.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 7/20/19 6:35PM
Publication Location:
Article Title: Quantum gradient descent and Newton's method for constrained polynomial optimization
Authors: Patrick Rebentrost, Maria Schuld, Leonard Wossnig, Francesco Petruccione, Seth Lloyd
Keywords: quantum algorithms
Abstract: Optimization problems in disciplines such as machine learning are commonly solved with iterative methods. Gradient descent algorithms find local minima by moving along the direction of steepest descent while Newton's method takes into account curvature information and thereby often improves convergence. Here, we develop quantum versions of these iterative optimization algorithms and apply them to polynomial optimization with a unit norm constraint. In each step, multiple copies of the current candidate are used to improve the candidate using quantum phase estimation, an adapted quantum state exponentiation scheme, as well as quantum matrix multiplications and inversions. The required operations perform polylogarithmically in the dimension of the solution vector and exponentially in the number of iterations. Therefore, the quantum algorithm can be useful for high-dimensional problems where a small number of iterations is sufficient.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: npj Quantum Information
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 5/19/20 6:38PM
Publication Location:
Article Title: Convex optimization of programmable quantum computers
Authors: Leonardo Banchi, Jason Pereira, Seth Lloyd, Stefano Pirandola
Keywords: quantum information
Abstract: A fundamental model of quantum computation is the programmable quantum gate array. This is a quantum processor that is fed by a program state that induces a corresponding quantum operation on input states. While being programmable, any finite-dimensional design of this model is known to be nonuniversal, meaning that the processor cannot perfectly simulate an arbitrary quantum channel over the input. Characterizing how close the simulation is and finding the optimal program state have been open questions for the past 20 years. Here, we answer these questions by showing that the search for the optimal program state is a convex optimization problem that can be solved via semidefinite programming and gradient-based methods commonly employed for machine learning. We apply this general result to different types of processors, from a shallow design based on quantum teleportation, to deeper schemes relying on port-based teleportation and parametric quantum circuits.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physcal Review Letters
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 3/12/19 6:42PM
Publication Location:
Article Title: Entropic Energy-Time Uncertainty Relation
Authors: Patrick J. Coles, Vishal Katariya, Seth Lloyd, Iman Marvian, Mark M. Wilde
Keywords: quantum information
Abstract: Energy-time uncertainty plays an important role in quantum foundations and technologies, and it was even discussed by the founders of quantum mechanics. However, standard approaches (e.g., Robertson's uncertainty relation) do not apply to energy-time uncertainty because, in general, there is no Hermitian operator associated with time. Following previous approaches, we quantify time uncertainty by how well one can read off the time from a quantum clock. We then use entropy to quantify the information-theoretic distinguishability of the various time states of the clock. Our main result is an entropic energy-time uncertainty relation for general time-independent Hamiltonians, stated for both the discrete-time and continuous-time cases. Our uncertainty relation is strong, in the sense that it allows for a quantum memory to help reduce the uncertainty, and this formulation leads us to reinterpret it as a bound on the relative entropy of asymmetry.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Research
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/8/20 12:00AM Date Published: 4/9/20 6:45PM
Publication Location:
Article Title: Dense coding capacity of a quantum channel
Authors: Riccardo Laurenza, Cosmo Lupo, Seth Lloyd, Stefano Pirandola
Keywords: Quantum communications
Abstract: We consider the fundamental protocol of dense coding of classical information assuming that noise affects both the forward and backward communication lines between Alice and Bob. Assuming that this noise is described by the same quantum channel, we define its dense coding capacity by optimizing over all adaptive strategies that Alice can implement, while Bob encodes the information by means of Pauli operators. Exploiting techniques of channel simulation and protocol stretching, we are able to establish the dense coding capacity of Pauli channels in arbitrary finite dimension, with simple formulas for depolarizing and dephasing qubit channels.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.105.022415
Volume: 105 Issue: 2 First Page #:
Date Submitted: Date Published: 2/1/22 3:00PM
Publication Location:
Article Title: Quantum advantage for differential equation analysis
Authors: Bobak Toussi Kiani, Giacomo De Palma, Dirk Englund, William Kaminsky, Milad Marvian, Seth Lloyd
Keywords: Quantum information
Abstract: Quantum algorithms for differential equation solving, data processing, and machine learning potentially offer an exponential speedup over all known classical algorithms. However, there also exist obstacles to obtaining this potential speedup in useful problem instances. The essential obstacle for quantum differential equation solving is that outputting useful information may require difficult postprocessing, and the essential obstacle for quantum data processing and machine learning is that inputting the data is a difficult task just by itself. In this study, we demonstrate that, when combined, these difficulties solve one another. We show how the output of quantum differential equation solving can serve as the input for quantum data processing and machine learning, allowing dynamical analysis in terms of principal components, power spectra, and wavelet decompositions. To illustrate this, we consider continuous-time Markov processes on epidemiological and social networks.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Transactions on Information Theory
Publication Identifier Type: DOI Publication Identifier: 10.1109/TIT.2021.3076442
Volume: 67 Issue: 10 First Page #: 6627
Date Submitted: 7/19/22 12:00AM Date Published: 10/1/21 12:00PM
Publication Location:
Article Title: The Quantum Wasserstein Distance of Order 1
Authors: Giacomo De Palma, Milad Marvian, Dario Trevisan, Seth Lloyd
Keywords: quantum information
Abstract: We propose a generalization of the Wasserstein distance of order 1 to the quantum states of n qudits. The proposal recovers the Hamming distance for the vectors of the canonical basis, and more generally the classical Wasserstein distance for quantum states diagonal in the canonical basis. The proposed distance is invariant with respect to permutations of the qudits and unitary operations acting on one qudit and is additive with respect to the tensor product. Our main result is a continuity bound for the von Neumann entropy with respect to the proposed distance, which significantly strengthens the best ontinuity bound with respect to the trace distance. We also propose a generalization of the Lipschitz constant to quantum observables. The notion of quantum Lipschitz constant allows us to compute the proposed distance with a semidefinite program.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Quantum Science and Technology
Publication Identifier Type: DOI Publication Identifier: 10.1088/2058-9565/ac79c9
Volume: 7 Issue: 4 First Page #:
Date Submitted: Date Published: 7/4/22 12:00PM
Publication Location:
Article Title: Learning quantum data with the quantum earth mover's distance
Authors: Bobak Toussi Kiani, Giacomo De Palma, Milad Marvian, Zi-Wen Liu, Seth Lloyd
Keywords: Quantum Information
Abstract: Quantifying how far the output of a learning algorithm is from its target is an essential task in machine learning. However, in quantum settings, the loss landscapes of commonly used distance metrics often produce undesirable outcomes such as poor local minima and exponentially decaying gradients. To overcome these obstacles, we consider here the recently proposed quantum earth mover's (EM) or Wasserstein-1 distance as a quantum analog to the classical EM distance. We show that the quantum EM distance possesses unique properties, not found in other commonly used quantum distance metrics, that make quantum learning more stable and efficient. We propose a quantum Wasserstein generative adversarial network (qWGAN) which takes advantage of the quantum EM distance and provides an efficient means of performing learning on quantum data.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.128.220502
Volume: 128 Issue: 22 First Page #:
Date Submitted: Date Published: 6/1/22 8:00AM
Publication Location:
Article Title: Quantum Algorithm for Petz Recovery Channels and Pretty Good Measurements
Authors: András Gilyén, Seth Lloyd, Iman Marvian, Yihui Quek, Mark M. Wilde
Keywords: Quantum Information
Abstract: The Petz recovery channel plays an important role in quantum information science as an operation that approximately reverses the effect of a quantum channel. The pretty good measurement is a special case of the Petz recovery channel, and it allows for near-optimal state discrimination. A hurdle to the experimental realization of these vaunted theoretical tools is the lack of a systematic and efficient method to implement them. This Letter sets out to rectify this lack: Using the recently developed tools of quantum singular value transformation and oblivious amplitude amplification, we provide a quantum algorithm to implement the Petz recovery channel when given the ability to perform the channel that one wishes to reverse.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.105.044141
Volume: 105 Issue: 4 First Page #:
Date Submitted: Date Published: 4/1/22 12:00PM
Publication Location:
Article Title: Quantum Maxwell's demon assisted by non-Markovian effects
Authors: Kasper Poulsen, Marco Majland, Seth Lloyd, Morten Kjaergaard, Nikolaj T. Zinner
Keywords: Quantum Information
Abstract: Maxwell's demon is the quintessential example of information control, which is necessary for designing quantum devices. In thermodynamics, the demon is an intelligent being who utilizes the entropic nature of information to sort excitations between reservoirs, thus lowering the total entropy. So far, implementations of Maxwell's demon have largely been limited to Markovian baths. In our work, we study the degree to which such a demon may be assisted by non-Markovian effects using a superconducting circuit platform. The setup is two baths connected by a demon-controlled qutrit interface, allowing the transfer of excitations only if the overall entropy of the two baths is lowered. The largest entropy reduction is achieved in a non-Markovian regime and, importantly, due to non-Markovian effects, the demon performance can be optimized through proper timing.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2204.00015
Publication Identifier Type: Other Publication Identifier: rXiv:2204.00015v1
Volume: Issue: First Page #:
Date Submitted: Date Published: 3/31/22 4:00AM
Publication Location:
Article Title: Measuring magic on a quantum processor
Authors: Salvatore FE Oliviero, Lorenzo Leone, Alioscia Hamma, Seth Lloyd
Keywords: Quantum Information
Abstract: Magic states are the resource that allows quantum computers to attain an advantage over classical computers. This resource consists in the deviation from a property called stabilizerness which in turn implies that stabilizer circuits can be efficiently simulated on a classical computer. Without magic, no quantum computer can do anything that a classical computer cannot do. Given the importance of magic for quantum computation, it would be useful to have a method for measuring the amount of magic in a quantum state. In this work, we propose and experimentally demonstrate a protocol for measuring magic based on randomized measurements. Our experiments are carried out on two IBM Quantum Falcon processors. This protocol can provide a characterization of the effectiveness of aquantum hardware in producing states that cannot be effectively simulated on a classical computer. We show how from these measurements one can construct realistic noise models affecting the hardware.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2203.05483
Publication Identifier Type: Publication Identifier: arXiv:2203.05483
Volume: Issue: First Page #:
Date Submitted: Date Published: 3/10/22 10:00AM
Publication Location:
Article Title: projUNN: efficient method for training deep networks with unitary matrices
Authors: Bobak Kiani, Randall Balestriero, Yann Lecun, Seth Lloyd
Keywords: Quantum Information
Abstract: In learning with recurrent or very deep feed-forward networks, employing unitary matrices in each layer can be very effective at maintaining long-range stability. However, restricting network parameters to be unitary typically comes at the cost of expensive parameterizations or increased training runtime. We propose instead an efficient method based on rank-k updates – or their rank-k approximation – that maintains performance at a nearly optimal training runtime. We introduce two variants of this method, named Direct (projUNN-D) and Tangent (projUNN-T) projected Unitary Neural Networks, that can parameterize full N-dimensional unitary or orthogonal matrices with a training runtime scaling as O(kN2).
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2201.11329
Publication Identifier Type: Other Publication Identifier: arXiv:2201.11329
Volume: Issue: First Page #:
Date Submitted: Date Published: 1/27/22 10:00AM
Publication Location:
Article Title: Quantum algorithm for dense and full-rank kernels using hierarchical matrices
Authors: Quynh T Nguyen, Bobak T Kiani, Seth Lloyd
Keywords: Quantum Information
Abstract: Kernel matrices, which arise from discretizing a kernel function k(x,x?), have a variety of applications in mathematics and engineering. Classically, the celebrated fast multipole method was designed to perform matrix multiplication on kernel matrices of dimension N in time almost linear in N by using techniques later generalized into the linear algebraic framework of hierarchical matrices. In light of this success, we propose a quantum algorithm for efficiently performing matrix operations on hierarchical matrices by implementing a quantum block-encoding of the hierarchical matrix structure. When applied to many physical kernel matrices, our quantum algorithm can solve quantum linear systems of dimension N in time O(?polylog(N?)), where ? and ? are the condition number and error bound of the matrix operation. This runtime is near-optimal and, in terms of N, exponentially improves over prior quantum linear systems algorithms for dense and full-rank kernel matrices.....
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2201.11329
Publication Identifier Type: Other Publication Identifier: arXiv:2201.11329
Volume: Issue: First Page #:
Date Submitted: Date Published: 1/27/22 10:00AM
Publication Location:
Article Title: Quantum algorithm for dense kernel matrices using hierarchical splitting
Authors: Quynh The Nguyen, Bobak Toussi Kiani, Seth Lloyd
Keywords: Quantum Information
Abstract: Kernel matrices, which arise from discretizing a kernel function k(x,x?), have a variety of applications in mathematics and engineering. Classically, the celebrated fast multipole method was designed to perform matrix multiplication on kernel matrices of dimension N in time almost linear in N by using techniques later generalized into the linear algebraic framework of hierarchical matrices. In light of this success, we propose a quantum algorithm for efficiently performing matrix operations on hierarchical matrices by implementing a quantum block-encoding of the hierarchical matrix structure. When applied to many physical kernel matrices, our quantum algorithm can solve quantum linear systems of dimension N in time O(?polylog(N?)), where ? and ? are the condition number and error bound of the matrix operation.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review X
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevX.12.011005
Volume: 12 Issue: 1 First Page #:
Date Submitted: Date Published: 1/1/22 10:00AM
Publication Location:
Article Title: Demonstration of Density Matrix Exponentiation Using a Superconducting Quantum Processor
Authors: M. Kjaergaard, M.E. Schwartz, A. Greene, G.O. Samach, A. Bengtsson, M. O'Keeffe, C.M. McNally, J. E
Keywords: Quantum Information
Abstract: Density matrix exponentiation (DME) is a general technique for using a quantum state ? to enact the quantum operation e?i?? on a target system. It was first proposed in the context of quantum machine learning, but has since been shown to have broad applications in quantum metrology and computation. No experimental demonstration of DME has been performed thus far due to its demanding circuit depths and the need to efficiently generate multiple identical copies of ? during the finite lifetime of the target system. In this work, we describe the first demonstration of the DME algorithm, which we accomplish using a superconducting quantum processor. Our demonstration relies on a 99.7% fidelity controlled-phase gate implemented using two tunable superconducting transmon qubits. We achieve a fidelity surpassing 90% at circuit depths exceeding 70 when comparing the output of the circuit executed on our quantum processor to a simulation assuming perfect operations and measurements.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2109.11330
Publication Identifier Type: Other Publication Identifier: arXiv preprint arXiv:2109.11330
Volume: Issue: First Page #:
Date Submitted: Date Published: 9/23/21 4:00AM
Publication Location:
Article Title: Quantum algorithms for group convolution, cross-correlation, and equivariant transformations
Authors: Grecia Castelazo, Quynh T Nguyen, Giacomo De Palma, Dirk Englund, Seth Lloyd, Bobak T Kiani
Keywords: Quantum Information
Abstract: Group convolutions and cross-correlations, which are equivariant to the actions of group elements, are commonly used in mathematics to analyze or take advantage of symmetries inherent in a given problem setting. Here, we provide efficient quantum algorithms for performing linear group convolutions and cross-correlations on data stored as quantum states. Runtimes for our algorithms are logarithmic in the dimension of the group thus offering an exponential speedup compared to classical algorithms when input data is provided as a quantum state and linear operations are well conditioned. Motivated by the rich literature on quantum algorithms for solving algebraic problems, our theoretical framework opens a path for quantizing many algorithms in machine learning and numerical methods that employ group operations.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Science Advances
Publication Identifier Type: DOI Publication Identifier: 10.1126/sciadv.abg2589
Volume: 7 Issue: 34 First Page #:
Date Submitted: Date Published: 8/1/21 8:00AM
Publication Location:
Article Title: Resonant quantum principal component analysis
Authors: Zhaokai Li, Zihua Chai, Yuhang Guo, Wentao Ji, Mengqi Wang, Fazhan Shi, Ya Wang, Seth Lloyd, Jian
Keywords: Quantum Information
Abstract: Principal component analysis (PCA) has been widely adopted to reduce the dimension of data while preserving the information. The quantum version of PCA (qPCA) can be used to analyze an unknown low-rank density matrix by rapidly revealing the principal components of it, i.e., the eigenvectors of the density matrix with the largest eigenvalues. However, because of the substantial resource requirement, its experimental implementation remains challenging. Here, we develop a resonant analysis algorithm with minimal resource for ancillary qubits, in which only one frequency-scanning probe qubit is required to extract the principal components. In the experiment, we demonstrate the distillation of the first principal component of a 4 × 4 density matrix, with an efficiency of 86.0% and a fidelity of 0.90. This work shows the speedup ability of quantum algorithm in dimension reduction of data and thus could be used as part of quantum artificial intelligence algorithms in the future.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: PRX Quantum
Publication Identifier Type: DOI Publication Identifier: 10.1103/PRXQuantum.2.030319
Volume: 2 Issue: 3 First Page #:
Date Submitted: Date Published: 8/1/21 8:00AM
Publication Location:
Article Title: Scalable and High-Fidelity Quantum Random Access Memory in Spin-Photon Networks
Authors: K. C. Chen, W. Dai, C. Errando-Herranz, S. Lloyd, D. Englund
Keywords: Quantum Information
Abstract: A quantum random access memory (qRAM) is considered an essential computing unit to enable polynomial speedups in quantum information processing. Proposed implementations include the use of neutral atoms and superconducting circuits to construct a binary tree but these systems still require demonstrations of the elementary components. Here, we propose a photonic-integrated-circuit (PIC) architecture integrated with solid-state memories as a viable platform for constructing a qRAM. We also present an alternative scheme based on quantum teleportation and extend it to the context of quantum networks. Both implementations realize the two key qRAM operations, (1) quantum state transfer and (2) quantum routing, with already demonstrated components: electro-optic modulators, a Mach-Zehnder interferometer (MZI) network, and nanocavities coupled to artificial atoms for spin-based memory writing and retrieval.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: PRX Quantum
Publication Identifier Type: DOI Publication Identifier: 10.1103/PRXQuantum.2.017001
Volume: 2 Issue: 1 First Page #:
Date Submitted: Date Published: 2/1/21 5:00AM
Publication Location:
Article Title: Quantum Computer Systems for Scientific Discovery
Authors: Yuri Alexeev, Dave Bacon, Kenneth R. Brown, Robert Calderbank, Lincoln D. Carr, Frederic T. Chong, I
Keywords: Quantum Information
Abstract: The great promise of quantum computers comes with the dual challenges of building them and finding their useful applications. We argue that these two challenges should be considered together, by codesigning full-stack quantum computer systems along with their applications in order to hasten their development and potential for scientific discovery. In this context, we identify scientific and community needs, opportunities, a sampling of a few use case studies, and significant challenges for the development of quantum computers for science over the next 2–10 years
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv:2206.08359v1
Publication Identifier Type: Publication Identifier: arXiv preprint arXiv:2206.08359
Volume: Issue: First Page #:
Date Submitted: Date Published: 6/16/22 4:00AM
Publication Location:
Article Title: Geometric Event-Based Relativistic Quantum Mechanics
Authors: Vittorio Giovannetti, Seth Lloyd, Lorenzo Maccone
Keywords: Quantum Information
Abstract: We propose a special relativistic framework for quantum mechanics. It is based on introducing a Hilbert space for events. Events are taken as primitive notions (as customary in relativity), whereas quantum systems (e.g. fields and particles) are emergent in the form of joint probability amplitudes for position and time of events. Textbook relativistic quantum mechanics and quantum field theory can be recovered by dividing the event Hilbert spaces into space and time (a foliation) and then conditioning the event states onto the time part. Our theory satisfies the full Poincare' symmetry as a `geometric' unitary transformation, and possesses observables for space (location of an event) and time (position in time of an event).
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2108.08855
Publication Identifier Type: Publication Identifier: arXiv preprint arXiv:2108.08855
Volume: Issue: First Page #:
Date Submitted: Date Published: 8/19/21 4:00AM
Publication Location:
Article Title: Non-markovian boost of quantum Maxwell demon efficiency
Authors: Kasper Poulsen, Marco Majland, Seth Lloyd, Morten Kjaergaard, Nikolaj T Zinner
Keywords: Quantum Information
Abstract: Maxwell's demon is the quintessential example of information control, which is necessary for designing quantum devices. In thermodynamics, the demon is an intelligent being who utilizes the entropic nature of information to sort excitations between reservoirs thus lowering the total entropy. So far, implementations of Maxwell's demon have largely been limited to Markovian baths. In our work, we study the degree to which such a demon may be assisted by non-Markovian effects using a superconducting circuit platform. The setup is two baths connected by a demon controlled qutrit interface, allowing the transfer of excitations only if the overall entropy of the two baths is lowered. Importantly, we show that non-Markovian effects yield the largest entropy reduction through appropriate timing of the demon operation. Our results demonstrate that non-Markovian effects can be exploited to boost the information transfer rate in quantum Maxwell demons.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2107.09200
Publication Identifier Type: Publication Identifier: arXiv preprint arXiv:2107.09200
Volume: Issue: First Page #:
Date Submitted: Date Published: 7/19/21 4:00AM
Publication Location:
Article Title: A quantum algorithm for training wide and deep classical neural networks
Authors: Alexander Zlokapa, Hartmut Neven, Seth Lloyd
Keywords: Quantum Information
Abstract: Given the success of deep learning in classical machine learning, quantum algorithms for traditional neural network architectures may provide one of the most promising settings for quantum machine learning. Considering a fully-connected feedforward neural network, we show that conditions amenable to classical trainability via gradient descent coincide with those necessary for efficiently solving quantum linear systems. We propose a quantum algorithm to approximately train a wide and deep neural network up to error for a training set of size by performing sparse matrix inversion in time. To achieve an end-to-end exponential speedup over gradient descent, the data distribution must permit efficient state preparation and readout. We numerically demonstrate that the MNIST image dataset satisfies such conditions; moreover, the quantum algorithm matches the accuracy of the fully-connected network.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 04-Aug-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2104.01410
Publication Identifier Type: Publication Identifier: arXiv:2104.01410v2
Volume: Issue: First Page #:
Date Submitted: Date Published: 4/3/21 4:00AM
Publication Location:
Article Title: Hamiltonian singular value transformation and inverse block encoding
Authors: Seth Lloyd, Bobak T Kiani, David RM Arvidsson-Shukur, Samuel Bosch, Giacomo De Palma, William M
Keywords: Quantum Information
Abstract: The quantum singular value transformation is a powerful quantum algorithm that allows one to apply a polynomial transformation to the singular values of a matrix that is embedded as a block of a unitary transformation. This paper shows how to perform the quantum singular value transformation for a matrix that can be embedded as a block of a Hamiltonian. The transformation can be implemented in a purely Hamiltonian context by the alternating application of Hamiltonians for chosen intervals: it is an example of the Quantum Alternating Operator Ansatz (generalized QAOA). We also show how to use the Hamiltonian quantum singular value transformation to perform inverse block encoding to implement a unitary of which a given Hamiltonian is a block. Inverse block encoding leads to novel procedures for matrix multiplication and for solving differential equations on quantum information processors in a purely Hamiltonian fashion.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2102.05767
Publication Identifier Type: Publication Identifier: arXiv:2102.05767
Volume: Issue: First Page #:
Date Submitted: Date Published: 2/10/21 5:00AM
Publication Location:
Article Title: Error mitigation via stabilizer measurement emulation
Authors: Ami Greene, M Kjaergaard, ME Schwartz, GO Samach, A Bengtsson, M O'Keeffe, DK Kim, M Marvian,
Keywords: Quantum Information
Abstract: Dynamical decoupling (DD) is a widely-used quantum control technique that takes advantage of temporal symmetries in order to partially suppress quantum errors without the need resource-intensive error detection and correction protocols. This and other open-loop error mitigation techniques are critical for quantum information processing in the era of Noisy Intermediate-Scale Quantum technology. However, despite its utility, dynamical decoupling does not address errors which occur at unstructured times during a circuit, including certain commonly-encountered noise mechanisms such as cross-talk and imperfectly calibrated control pulses. Here, we introduce and demonstrate an alternative technique - `quantum measurement emulation' (QME) - that effectively emulates the measurement of stabilizer operators via stochastic gate application, leading to a first-order insensitivity to coherent errors.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2011.06571
Publication Identifier Type: Publication Identifier: arXiv:2011.06571
Volume: Issue: First Page #:
Date Submitted: Date Published: 11/12/20 10:31PM
Publication Location:
Article Title: Quantum algorithm for nonlinear differential equations
Authors: Seth Lloyd, Giacomo De Palma, Can Gokler, Bobak Kiani, Zi-Wen Liu, Milad Marvian, Felix Tennie, Tim
Keywords: Quantum Information
Abstract: Quantum computers are known to provide an exponential advantage over classical computers for the solution of linear differential equations in high-dimensional spaces. Here, we present a quantum algorithm for the solution of nonlinear differential equations. The quantum algorithm provides an exponential advantage over classical algorithms for solving nonlinear differential equations. Potential applications include the Navier-Stokes equation, plasma hydrodynamics, epidemiology, and more.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: arXiv preprint arXiv:2004.02036
Publication Identifier Type: Publication Identifier: arXiv:2004.02036
Volume: Issue: First Page #:
Date Submitted: Date Published: 4/4/20 4:00AM
Publication Location:
Article Title: Quantum medical imaging algorithms
Authors: Bobak Toussi Kiani, Agnes Villanyi, Seth Lloyd
Keywords: Quantum Information
Abstract: A central task in medical imaging is the reconstruction of an image or function from data collected by medical devices (e.g., CT, MRI, and PET scanners). We provide quantum algorithms for image reconstruction with exponential speedup over classical counterparts when data is input as a quantum state. Since outputs of our algorithms are stored in quantum states, individual pixels of reconstructed images may not be efficiently accessed classically; instead, we discuss various methods to extract information from outputs using a variety of quantum post-processing algorithms.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Partners

,

RPPR Final Report
as of 04-Aug-2022

I certify that the information in the report is complete and accurate:
Signature: Seth Lloyd
Signature Date: 7/26/22 9:55AM

ARO Final Performance Report Project Title: Quantum Machine Learning

Award Number:

W911NF-17-1-0527

Program Officer:

Sara Gamble

Principal Investigator:

Seth Lloyd

Participants:

Seth Lloyd (PI): Professor of Mechanical Engineering, MIT

Peter Shor: Professor of Mathematics and Computer Science, MIT

Dirk Englund: Professor of Electrical Engineering and Computer Science, MIT

Will Oliver: Professor of Electrical Engineering and Computer Science, MIT

Stefano Pirandola: Professor of Physics, University of York

Patrick Rebentrost: Postdoctoral Fellow, MIT (now Research Associate Professor, National University of Singapore)

Iman Marvian: Postdoctoral Fellow, MIT (now Assistant Professor of Physics and Electrical Engineering, Duke University)

Giacomo De Palma: Postdoctoral Fellow, MIT (now Assistant Professor of Mathematics, University of Bologna)

Milad Marvian: Postdoctoral Fellow, MIT (now Assistant Professor of Physics and Computer Science, University of New Mexico)

Zi-Wen Liu: Graduate Student, MIT (now Researcher, Perimeter Institute)

Can Gokler: Graduate Student, Harvard

Keven Thompson: Graduate Student, Harvard

Reevu Maity: Graduate Student, Oxford/MIT

Bobak Kiani: Graduate Student, MIT

Ryuji Takagi: Graduate Student, MIT

Oles Shtanko: Graduate Student, MIT

Grecia Castelazo: Graduate Student, MIT

Samuel Bosch: Graduate Student, MIT

Lara Booth: Graduate Student, Oxford/MIT

David Arvidsson-Shukur: Fellow, Cambridge; Visiting Scholar, MIT

Principle activities and findings:

The research supported by this grant focused on problems of quantum machine learning: how do you load data onto a quantum computer, and process it to reveal patterns that classical computers can't find? When the grant commenced, in 2017, the field of quantum machine learning was in its infancy. There were a few results on quantum algorithms for clustering, principal component analysis, and topological analysis of data, as well as designs for quantum random access memory (qRAM): but quantum machine learning had yet to emerge as an established discipline of scientific study.

In the intervening five years, the field of quantum machine learning has expanded dramatically. The work supported by this grant played a key role in several branches of quantum machine learning. (See our review paper, reference [1], for a general description of the field. This work, one of the first works supported by the grant, has become the central reference and the most highly cited paper in the field of quantum machine learning.)

(1) Quantum generative adversarial networks (qGAN):

We established the paradigm of quantum generative adversarial networks (qGAN), in which a quantum generator tries to generate data that can deceive a quantum discriminator [26]. We proved the convergence of such networks to optimal solutions, and showed how quantum generative networks can substantially out-perform classical generative networks.

(2) Quantum neural networks:

Prior to 2017, there was no accepted general definition for the quantum neural networks. We established the now-accepted design and framework for continuous variable quantum neural networks [20,40]. We provided the first design for quantum recurrent neural networks [12]. We showed how a quantum Hopfield network can provide exponential advantages over classical Hopfield networks [24]. We developed a quantum algorithm for simulating the neural tangent kernel and for training large neural networks [62].

(3) Quantum differential equation solvers:

Because of their ability to represent 2_n dimensional vectors as the state of n qubits, quantum computers have the potential for solving differential equations exponentially more efficiently than classical computers. We provided the first formulation for solving continuous variable differential equations by showing how to invert infinite-dimensional operators [23,39]. We showed how quantum computers can reveal non-trivial features of the solutions of differential equations by performing quantum post-processing [53,68].

Finally, we showed how quantum computers can be used to solve nonlinear differential equations by using interactions between multiple copies of the system [54], in analogue to the use of non-linear Schr¨odinger equations to describe the behavior of Bose-Einstein condensates.

(4) Quantum algorithms for machine learning

Over the course of the program, we developed a number of novel quantum algorithms focused on machine learning and data analysis. We developed efficient quantum algorithms for spectral estimation [2], for Gaussian hypothesis testing [14], for quantum- singular value decomposition [15], for portfolio optimization [27], for gradient descent and Newton’s method [38], for medical imaging [48], for performing the matrix polar decom- position [50], and for pretty good measurements and channel decoding [51,71].

We developed quantum algorithms for group convolution, cross correlation, and equivariant transformations [65] – i.e., for the central algebraic methods underlying the analysis of data with symmetries.

We established the basic methods for quantum kernel analysis, in which classical data is embedded as quantum states in a high-dimensional Hilbert space, and optimal quantum measurements are then performed to discriminate between clusters of data [46].

We showed how problems of barren plateaus in variational quantum algorithms can be avoided by using a quantum version of Earth-Mover's (Wasserstein 1) distance [55,60].

(5) Quantum inspired algorithms

The potential for quantum inspired algorithms was first pointed out by Ewin Tang in 2018, who noted that the quantum principal component analysis algorithm for low-rank matrices could be simulated classically using existing low-rank matrix techniques. Together with Andras Gilyen, we showed how quantum inspired techniques could be extended to matrix inversion and the quantum singular value transform for low rank matrices [28], and we performed detailed simulations of how such quantum inspired algorithms would play out when applied to very large classical data sets [37].

(6) Classical deep learning

We applied methods from quantum computing to derive several results in the field of classical deep learning. First, we showed that classical deep neural networks are biased towards functions that are simple and robust [30,45]. Next, in collaboration with Yann Lecun, we showed how the linear transformations of deep neural networks can be replaced with unitary transformations, with attendant improvements on performance and convergence [73].

7. Quantum sensing and control

We developed applications of quantum sensing and control to quantum machine learning, with the goal of finding and taking advantage of patterns in the behavior of quantum systems. We investigated geometric methods of quantum control [4], methods for the quantum control of graphical systems [13], photonic quantum sensing [29], entanglement enhanced sensing via post-selection [34,52], and non-Markovian effects in quantum measurement [74].

8. Experimental collaborations

During the course of the grant, we developed experimental applications of the fun- damental ideas developed by the theoretical efforts. In particular, our ideas on quantum walks and quantum transport on complex graphs were realized experimentally in the context of photonics by Dirk Englund's group [10,11], and in the context of excitonic transport by Moungi Bawendi's group [18,25]. Our work on quantum principal component analysis and density matrix exponentiation was realized experimentally by Will Oliver [42,47,67]. The Englund group also realized our method for variational learning of quantum circuits [47], and we collaborated on the experimental design of qRAM [58,63].

The Englund and Oliver groups are continuing with experimental demonstrations of our work on quantum circuits, qGANs, and qRAM.

Publications supported by this grant:

1. J. Biamonte, P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, S. Lloyd, 'Quantum machine learning,' *Nature* **549** (7671), 195-202 (2017).

2. A. Steffens, P. Rebentrost, I. Marvian, J. Eisert, S. Lloyd, 'An efficient quantum algorithm for spectral estimation,' *New Journal of Physics* **19**(3) 033005 (2017).

3. Z.W. Liu, X. Hu, S. Lloyd, 'Resource Destroying Maps,' *Physical Review Letters* **118** (6), 060502 (2017).

4. X. Wang, M. Allegra, K. Jacobs, S. Lloyd, C,. Lupo, M. Mohseni, 'Time-optimal quantum control via differential geometry,' *Advances in Photonics of Quantum Computing, Memory, and Communication X* **10118**, 53-59 (2017).

5. S. Lloyd, P. Shor, K. Thompson, 'polylog-LDPC Capacity Achieving Codes for the Noisy Quantum Erasure Channel,' arXiv: 1703.00382.

6. Z.W. Liu, S. Lloyd, E.Y. Zhu, H. Zhu, 'Entropic scrambling complexities,' arXiv: 1703.08104.

7. A. Kolchinsky, I. Marvian, C. Gokler, Z.W. Liu, P. Shor, O. Shtanko, K. Thompson, D. Wolpert, S. Lloyd, 'Maximizing free energy gain,' arXiv: 1705.00041.

8. C. Gokler, A. Kolchinsky, Z.W. Liu, I. Marvian, P. shor, O. Shtanko, K. Thompson, D. Wolpert, S. Lloyd, 'When is a bit worth much more than kT ln2?' arXiv: 1705.09598.

9. Z.W. Liu, R. Takagi, S. Lloyd, 'On diagonal discord,' arXiv:1708.09076.

10. Jelena Notaros, Jacob Mower, Mikkel Heuck, Cosmo Lupo, Nicholas C Harris, Gregory R Steinbrecher, Darius Bunandar, Tom Baehr-Jones, Michael Hochberg, Seth Lloyd, Dirk Englund, 'Programmable dispersion on a photonic integrated circuit for classical and quantum applications,' *Optics Express* **25**, 21275-21285 (2017).

11. Nicholas C Harris, Gregory R Steinbrecher, Mihika Prabhu, Yoav Lahini, Jacob Mower, Darius Bunandar, Changchen Chen, Franco NC Wong, Tom Baehr-Jones, Michael Hochberg, Seth Lloyd, Dirk Englund, 'Quantum transport simulations in a programmable nanophotonic processor,' 1*Nature Photonics* **11**, 447 (2017).

12. Patrick Rebentrost, Thomas R Bromley, Christian Weedbrook, Seth Lloyd, 'A Quantum Recurrent Neural Network.' arXiv: 1710.03599.

13. C. Gokler, S. Lloyd, P. Shor, K. Thompson 'Efficiently controllable graphs,' *Physical Review Letters* **118**, 260501 (2017).

14. M.M. Wilde, M. Tomamichel, S. Lloyd, M. Berta, 'Gaussian hypothesis testing and quantum illumination,' *Physical Review Letters* **119**, 120501 (2017).

15. P. Rebentrost, A. Steffens, I. Marvian, S. Lloyd, 'Quantum singular-value decomposition of nonsparse low-rank matrices,' *Physical Review A* **97**, 01232 (2018).

16. Zi-Wen Liu, Seth Lloyd, Elton Yechao Zhu, Huangjun Zhu, 'Generalized entanglement entropies of quantum designs,' *Phys. Rev. Lett.* **120**, 130502 (2018).

17. S. Lloyd, C. Weedbrook, ‘Quantum generative adversarial learning,’ *Physical Review Letters* **121** (4), 040502 (2018).

18. Sandra Doria, Timothy S Sinclair, Nathan D Klein, Doran IG Bennett, Chern Chuang, Francesca S Freyria, Colby P Steiner, Paolo Foggi, Keith A Nelson, Jianshu Cao, Alan Aspuru-Guzik, Seth Lloyd, Justin R Caram, Moungi G Bawendi, ‘Photochemical Control of Exciton Superradiance in Light-Harvesting Nanotubes,’ ACS Nano 12, 4556-4564 (2018).

19. PJ Coles, V Katariya, S Lloyd, I Marvian, MM Wilde, ‘Entropic Energy-Time Uncertainty Relation,’ arXiv: 1805.07772.

20. N Killoran, TR Bromley, JM Arrazola, M Schuld, N Quesada, S Lloyd, ‘Continuous-variable quantum neural networks,’ arXiv: 1806.06871.

21. ZW Liu, S Lloyd, E Zhu, H Zhu, ‘Entanglement, quantum randomness, and complexity beyond scrambling,’ Journal of High Energy Physics 2018 (7), 1-62 (2018).

22. O Shtanko, S Lloyd, ‘Hydrodynamic behavior of non-interacting quantum particles in presence of dephasing,’ arXiv: 1807.07087.

23. JM Arrazola, T Kalajdzievski, C Weedbrook, S Lloyd, ‘Quantum algorithm for non-homogeneous linear partial differential equations,’ arXiv: 1809.02622.

24. P Rebentrost, TR Bromley, C Weedbrook, S Lloyd, ‘Quantum Hopfield neural network,’ *Physical Review A* **98**, 042308 (2018).

25. S Doria, TS Sinclair, ND Klein, DIG Bennett, C Chuang, FS Freyria, CP Steiner, P Foggi, KA Nelson, J Cao, A Aspuru-Guzik, S Lloyd, JR Caram, MG Bawendi, 'Photochemical control of exciton superradiance in light-harvesting nanotubes,' *ACS nano* **12** (5), 4556-4564 (2018).

26. S Lloyd, C Weedbrook, 'Quantum generative adversarial learning,' *Physical Review Letters* **121**(4), 040502 (2018).

27. P Rebentrost, S Lloyd, 'Quantum computational finance: quantum algorithm for portfolio optimization,' arXiv:1811.03975 (2018).

28. A Gilyen, S Lloyd, E Tang, 'Quantum-inspired low-rank stochastic regression with logarithmic dependence on the dimension,' arXiv:1811.04909 (2018).

29. S Pirandola, BR Bardhan, T Gehring, C Weedbrook, S Lloyd 'Advances in photonic quantum sensing,' *Nature Photonics* **12** (12), 724-733 (2018).

30. G. De Palma, BT Kiani, S Lloyd, 'Random deep neural networks are biased towards simple functions,' *Advances in Neural Information Processing Systems* **32** (2019); arXiv: 1812.10156 (2018).

31. S Lloyd, 'Quantum approximate optimization is computationally universal,' arXiv: 1812.11075 (2018).

32. S Lloyd, R Maity, 'Efficient implementation of unitary transformations,' arXiv: 1901.03431 (2018).

33. ZW Liu, R Takagi, S Lloyd, ‘Diagonal quantum discord,’ *Journal of Physics A: Mathematical and Theoretical* **52** (13), 135301 (2019).

34. DRM Arvidsson-Shukur, N Yunger Halpern, HV Lepage, AA Lasek, CHW Barnes, S Lloyd, ‘Quantum negativity provides advantage in postselected metrology,’ arXiv: 1903.02563 (2019).

35. PJ Coles, V Katariya, S Lloyd, I Marvian, MM Wilde, ‘Entropic energy-time uncertainty relation,’ *Physical Review Letters* **122** (10), 100401 (2019).

36. L Banchi, J Pereira, S Lloyd, S Pirandola, ‘Optimization and learning of quantum programs,’ arXiv:1905.01318 (2019).

37. J.M. Arrazola, A. Delgado, B.R. Bardhan, S. Lloyd, ‘Quantum-inspired algorithms in practice,’ arXiv: 1905.10415 (2019), *Quantum* **4**, 307 (2020).

38. P. Rebentrost, M. Schuld, L. Wossnig, F. Petruccione, S. Lloyd, ‘Quantum gradient descent and Newton’s method for constrained polynomial optimization,’ *New Journal of Physics* **21** (7), 073023 (2019).

39. JM Arrazola, T Kalajdzievski, C Weedbrook, S Lloyd, ‘Quantum algorithm for non-homogeneous linear partial differential equations,’ *Physical Review A* **100** (3), 032306 (2019).

40. N Killoran, TR Bromley, JM Arrazola, M Schuld, N Quesada, S Lloyd, ‘Continuous-variable quantum neural networks,’ *Physical Review Research* **1** (3), 033063 (2019).

41. M Marvian, S Lloyd, ‘Robust universal Hamiltonian quantum computing using two-body interactions,’ arXiv:1911.01354 (2019).

42. M Kjaergaard, M Schwartz, A Greene, G Samach, A Bengtsson, M OKeeffe, C McNally, J Braumller, D Kim, P Krantz, M Marvian, A Melville, BM Niedzielski, Y Sung, R Winik, J Yoder, D Rosenberg, K Obenland, S Lloyd, TP Orlando, I Marvian, S Gustavsson, WD Oliver, ‘A quantum instruction set implemented on a superconducting quantum processor,’ arXiv:2001.08838 (2019).

43. B Toussi Kiani, S Lloyd, R Maity, ‘Learning Unitaries by Gradient Descent,’ arXiv: 2001.11897 (2020).

44. B Leonardo, J Pereira, S Lloyd, S Pirandola, ‘Convex optimization of programmable quantum computers,’ NPJ Quantum Information 6 (1) (2020).

45. NH Chia, A Gilyen, HH Lin, S Lloyd, E Tang, C Wang, ‘Quantum-inspired algorithms for solving low-rank linear equation systems with logarithmic dependence on the dimension,’ 31st International Symposium on Algorithms and Computation (ISAAC 2020).

46. S Lloyd, M Schuld, A Ijaz, J Izaac, N Killoran, ‘Quantum embeddings for machine learning,’ arXiv: 2001.03622 (2020).

47. J Carolan, M Mohseni, JP Olson, M Prabhu, C Chen, D Bunandar, MY Niu, NC Harris, FNC Wong, M Hochberg, S Lloyd, D Englund, ‘Variational quantum unsampling on a quantum photonic processor,’ *Nature Physics* **16** (3), 322-327 (2020).

48. B Toussi Kiani, A Villanyi, S Lloyd, ‘Quantum Medical Imaging Algorithms,’ arXiv: 2004.02036 (2020).

49. L Sun, X He, C You, C Lv, B Li, S Lloyd, X Wang, ‘Exponentially enhanced quantum metrology using resources of linear complexity,’arXiv: 2004.01216 (2020).

50. S Lloyd, S Bosch, G De Palma, B Kiani, ZW Liu, M Marvian, P Rebentrost, ‘Quantum polar decomposition algorithm,’ arXiv:2006.00841 (2020).

51. A Gilyen, S Lloyd, I Marvian, Y Quek, MM Wilde, ‘Quantum algorithm for Petz recovery channels and pretty good measurements,’ arXiv:2006.16924 (2020).

52. DRM Arvidsson-Shukur, NY Halpern, HV Lepage, AA Lasek, CHW Barnes, S Lloyd, ‘Quantum advantage in postselected metrology,’ *Nature Communications* **11** (1), 1-7 (2021).

53. BT Kiani, G De Palma, D Englund, W Kaminsky, M Marvian, S Lloyd, ‘Quantum advantage for differential equation analysis,’ arXiv:2010.15776 (2021)

54. S Lloyd, G De Palma, C Gokler, B Kiani, ZW Liu, M Marvian, F Tennie, T Palmer, ‘Quantum algorithm for nonlinear differential equations,’ arXiv:2011.06571 (2021).

55. BT Kiani, G De Palma, M Marvian, ZW Liu, S Lloyd, ‘Quantum Earth Mover’s Distance: A New Approach to Learning Quantum Data,’ arXiv:2101.03037 (2021).

56. A Greene, M Kjaergaard, ME Schwartz, GO Samach, A Bengtsson, M O'Keeffe, DK Kim, M Marvian, A Melville, BM Niedzielski, A Vepsalainen, R Winik, J Yoder, D Rosenberg, S Lloyd, TP Orlando, I Marvian, S Gustavsson, WD Oliver, 'Error mitigation via stabilizer measurement emulation,' arXiv:2102.05767 (2021).

57. Y Alexeev, D Bacon, KR Brown, R Calderbank, LD Carr, FT Chong, B DeMarco, D Englund, E Farhi, B Fefferman, AV Gorshkov, A Houck, J Kim, S Kimmel, M Lange, S Lloyd, MD Lukin, D Maslov, P Maunz, C Monroe, J Preskill, M Roetteler, MJ Savage, J Thompson, 'Quantum computer systems for scientific discovery,' *PRX Quantum* **2** (1), 017001 (2021).

58. KC Chen, W Dai, C Errando-Herranz, S Lloyd, D Englund, 'Scalable and High-Fidelity Quantum Random Access Memory in Spin-Photon Networks,' arXiv: 2103.07623 (2021).

59. S Lloyd, BT Kiani, DRM Arvidsson-Shukur, S Bosch, G De Palma, WM Kaminsky, ZW Liu, M Marvian, 'Hamiltonian singular value transformation and inverse block encoding,' arXiv:2104.01410 (2021).

60. G De Palma, M Marvian, D Trevisan, S Lloyd, 'The quantum Wasserstein distance of order 1,' IEEE Transactions on Information Theory (2021).

61. G De Palma, B Kiani, S Lloyd, 'Adversarial robustness guarantees for random deep neural networks,' *International Conference on Machine Learning,* 2522-2534 (2021).

62. A. Zlokapa, H. Neven, S. Lloyd, 'A quantum algorithm for training wide and deep neural networks,' arXiv: 2107.09200 (2021).

63. K.C. Chen, W. Dai, C. Errando-Herranz, S. Lloyd, D. Englund, ‘Scalable and High-Fidelity Quantum Random Access Memory in Spin-Photon Networks,’ *PRX Quantum* **2**, 030319 (2021).

64. Z. Li, Z. Chai, Y. Guo, W. Ji, M. Wang, F. Shi, Y. Wang, S. Lloyd, J. Du, ‘Resonant quantum principal component analysis,’ *Science Advances* **7** (34), eabg2589 (2021).

65. G. Castelazo, Q.T. Nguyen, G. De Palma, D. Englund, S. Lloyd, B.T. Kiani, ‘Quantum algorithms for group convolution, cross-correlation, and equivariant transformations,’ arXiv: 2109.11330 (2021).

66. Q.T. Ngyuen, B.T. Kiani, S. Lloyd, ‘Quantum algorithm for dense kernel matrices using hierarchical splitting,’ arXiv: 2201.11329 (2022).

67. M. Kjaergaard, M.E. Schwartz, A. Greene, G.O. Samach, A. Bengtsson, M. OKeeffe, C.M. McNally, J. Braumuller, D.K. Kim, P. Krantz, M. Marvian, A. Melville, B.M. Niedzielski, Y. Sung, R. Winik, J. Yoder, D. Rosenberg, K. Obenland, S. Lloyd, T.P. Orlando, I. Marvian, S. Gustavsson, W.D. Oliver, ‘Demonstration of density matrix exponentiation using a superconducting quantum processor,’ *Physical Review X* **12** (1), 011005 (2022).

68. B.T. Kiani, G. De Palma, D. Englund, W. Kaminsky, M. Marvian, S. Lloyd ‘Quantum advantage for differential equation analysis,’ *Physical Review A* **105** (2), 022415 (2022).

69. B.T. Kiani, G. De Palma, M. Marvian, Z.W. Liu, S. Lloyd, `Learning quantum data with the quantum Earth Mover’s distance,’ *Quantum Science and Technology* **7**, 045002 (2022).

70. V Giovannetti, S Lloyd, L Maccone ‘Geometric Event-Based Relativistic Quantum Mechanics,’ arXiv: 2206.08359 (2022).

71. A. Gilýen, S. Lloyd, I. Marvian, Y. Quek, M.M. Wilde, ‘Quantum algorithm for Petz recovery channels and pretty good measurements,’ *Physical Review Letters* **128**(22), 220502 (2022).

72. S.F.E. Oliviero, L. Leone, A. Hamma, S. Lloyd, ‘Measuring magic on a quantum processor,’ arXiv: 2204.00015 (2022).

73. B. Kiani, R. Balestriero, Y. Lecun, S. Lloyd, ‘projUNN: efficient method for training deep networks with unitary matrices,’ arXiv: 2203.0548 (2022).

74. K. Poulsen, M. Majland, S. Lloyd, M. Kjaergaard, N.T. Zinner, ‘Quantum Maxwell’s demon assisted by non-Markovian effects,’ *Physical Review E* **105**(4), 044141 (2022).