

## Quantum Algorithms Program

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### PROGRAM DESCRIPTION

This programme aims to help us understand better the ultimate capabilities of a quantum computer. In this programme we explore new applications of quantum information devices and these may range from applications that have direct benefit to scalable quantum computation through to new applications which might more immediately benefit small scale quantum processors. In the former category the most significant of these are new quantum algorithms that outperform their classical counter part. However novel methods for quantum information transport, novel architectures for quantum computation, novel designs for fault resistant quantum computation and methods for fast quantum control also benefit scalable quantum computation. Towards quantum processing with smaller numbers of qubits one can consider novel small scale quantum protocols such as quantum random walks and quantum metrology. Such small scale protocols may be considered as stepping stones towards larger protocols. The work of this programme combines skills from mathematical physics, computer science, and statistics, through to collaborative projects between the theory researchers and experimentalists in quantum optics and condensed matter quantum science.

Much of today's efforts in quantum computation were motivated by Peter Shor's discovery in 1994 of a quantum algorithm which can factor large integers exponentially faster than the best known classical algorithm. Since then it has

become clear that discovering new quantum algorithms to solve such number theoretic problems is exceedingly difficult and only a few quantum algorithms displaying exponential speed ups have been discovered since. Many algorithms which display a quadratic speed up have been discovered (e.g. Grover's algorithm), but the burning goal is to uncover more exponentially fast quantum algorithms. With I. Shparlinski, we have discovered a quantum algorithm which solves a certain number theoretic problem which displays a cubic speed up as compared with the best known classical algorithm. This intermediate quantum algorithm might help researchers understand better the different classes of quantum algorithms discovered to date (exponential-through to -quadratic), and may point the way towards more discoveries of exponentially fast quantum algorithms.

One class of problem – the graph isomorphism problem – is an example which still eludes the formulation of an efficient quantum algorithm. Research into this problem has led to deeper insights into the properties of quantum evolution on graphs. Graphs, whose adjacency matrix possess eigenvalues which are arranged in a regular pattern (like the integers), exhibit very special quantum transport properties. With C. Facer, J. Cresser and J. Twamley we found a family of graphs (Cayley graphs – which are  $d$ -dimensional hypercubes with additional links), which exhibit the very useful property of perfect quantum transport, i.e. quantum information injected on an input node of the network disperses over the entire graph but at a given time in the future it rephases perfectly to a preset output node. Such a design might be useful for routing quantum information within a device. With I. Shparlinski we found a wider class

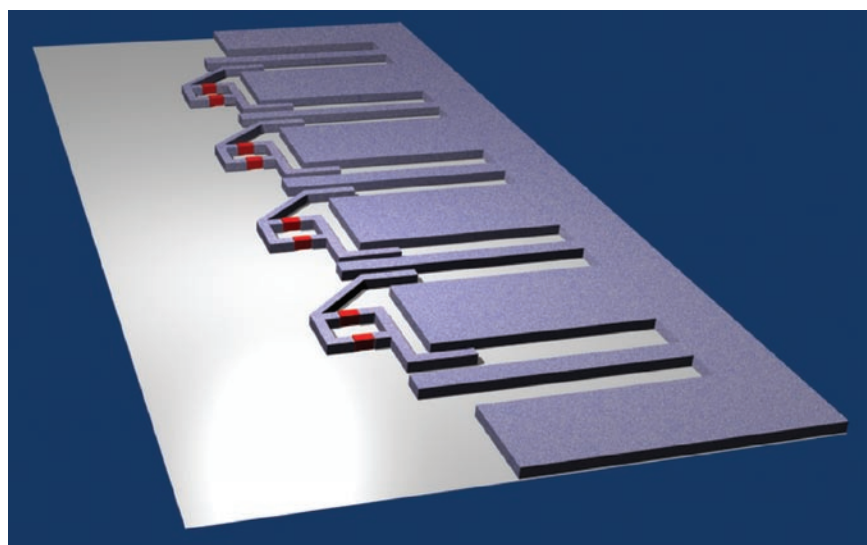


FIGURE 1

From the work reported in [G.A. Paz-Silva, S. Rebic, J. Twamley and T. Duty, Phys. Rev. Lett. 102, 020503 (2009)], where we show in theory how the quantum state of a chain of oscillators can be spatially mirrored through the application of global pulses. Here the oscillators correspond to the quantised microwave photons held in the quarter wave superconducting coplanar resonators and these are connected by switchable Cooper-Pair boxes.

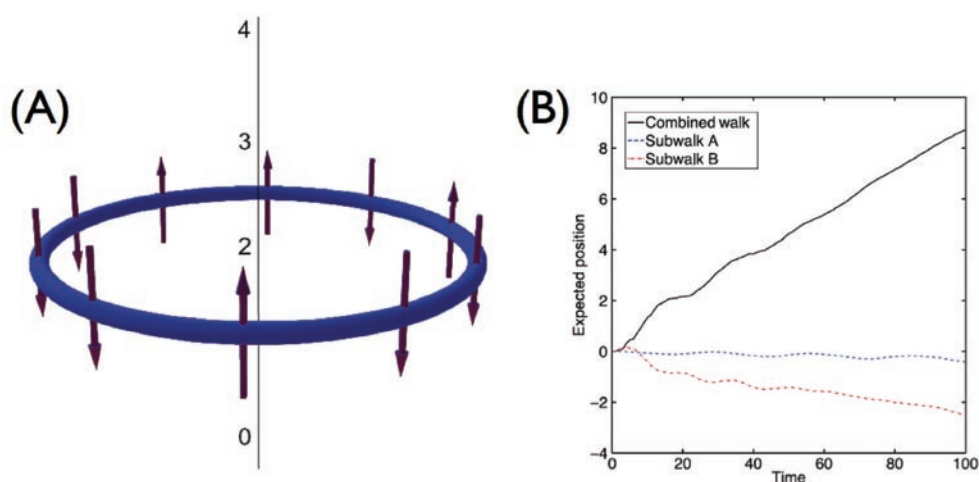


FIGURE 2

From the work reported in [D. Bulger *et al.*, New J Phys 10, 093014 (2008)]. Figure (A) is a schematic of a cooperative Parrondo game where a ring executes a quantum random walk along a vertical line but where the individual step up or down is decided by the players on the ring in a cooperative manner. In each step a player is chosen to move the ring. She makes her decision according to either two strategies (1) Subwalk A or (2) Subwalk B, and each is cooperative, i.e. each decision strategy depends on the states of her neighbouring arrows. If she only uses one of the two strategies the ring, on average, moves towards the negative direction while if she switches between strategies the ring, on average, moves towards the positive direction.

of graphs that display such curious perfect quantum transport properties.

Quantum transport of a single particle on simple graphs (e.g. the 1D line), which is conditioned on the state of some internal state of the particle which also evolves is a type of quantum analogue of the *random walk*. The quantum random walk has received much study over the past few years towards developing quantum versions of classical stochastic algorithms. With J. Freckleton, D. Bulger and J. Twamley we studied quantum versions of the Parrondo paradoxical game. The Parrondo game is a game where a player initially possesses a given amount of money and can gamble via two types of strategies. If he plays either strategy continually he is guaranteed to lose all his money eventually while if he switches, even randomly, between each type of strategy, he is guaranteed to always increase his money eventually. We were able to expand previous work on the quantum version of this paradoxical game to a multiplayer cooperative game which again exhibits paradoxical behaviour with regard to continually playing a single strategy or if they can switch between strategies.

Developing good strategies to protect the quantum processor from noise will be a vital ingredient for any large quantum processor. One strategy is to encode quantum information in a subspace that is insensitive to the ever-present quantum noise. Such “decoherence free subspaces”, have been the focus of much research worldwide and with P. Brook, J. Cresser, and B.C. Sanders we have examined this method of quantum noise avoidance for a collection of closely-spaced interacting dipoles (e.g. atoms). Besides introducing quantum noise,

coupling to the environment also produces an extra unwanted unitary evolution (like the Lamb-shift), which can cause the encoded quantum information to evolve out of the protected decoherence free subspace. In his thesis work P. Brooke found a particular encoding of the quantum information of four dipole-coupled atoms which was immune to both the non-unitary and unitary effects of the coupling to the environment.

One typically uses quantum process tomography to deduce the fidelity of quantum operations in a real-world device. When one performs such tomography one typically obtains a non-completely positive quantum operation. Until recently it was considered that such a quantum operation was unphysical and the aberrant result was a consequence of experimental inaccuracies in the measurements. Previously one *fixed up* this supposedly unphysical map by searching for the closest completely-positive quantum operation. Following on from recent results elsewhere, with C. Woods, D. Terno, A. Gilchrist, we found that non-completely-positive quantum operations could have a physical interpretation other than from experimental inaccuracies. One example which might be *much more typical than previously considered* is when there exists initial correlations between the system and environment. We are working on ways to identify when a non-completely process which is the result of a quantum process tomogram of quantum device is due to experimental inaccuracy or is due to initial unwanted correlation. Solving this will help in improving our gate characterization and initial state preparations.

The design of novel architectures for improved quantum control can lead to

great leaps in development. By encoding quantum information into topological degrees of freedom which are immune to any errors acting locally, one can design a type of *built-in hardware resilience* to quantum noise in the quantum processor. Topological quantum operations can (in theory), be achieved with anyons (particles which have neither fermion or bosonic statistics but possess more general statistics), but such exotic particles have yet to be discovered in nature. With G. Brennen we showed how anyonic particles could be simulated in atoms held and manipulated in an optical lattice. One can also protect against errors by making errors energetically costly. With G. Brennen we developed a type of *measurement based* quantum computing scheme where the quantum computational states are engineered to have an *energy gap* to the next highest level, thus exponentially suppressing errors in the model. Reducing the amount of control required for a quantum computation may also lead to great simplifications in the classical control circuitry and also possibly the error rate. With G. Paz-Silva, S. Rebic, T. Duty and J. Twamley we discovered a protocol to spatially mirror the state of a 1D chain of quantum chain using only global (homogenous), pulses and found a scheme to implement this using the recent technology of Circuit-QED. Interestingly the protocol works for quantum systems of arbitrary dimension, i.e. a chain of CV (infinite dimension), quantum systems and we. We have developed this into a scheme to perform universal quantum computation on a 1D chain of quantum systems with arbitrary internal dimensions using only global pulses.