Computer Science Project: Report 2013-2014

I. INTRODUCTION

In 2014 Troy Lee became the 4th PI of the CS group. With his arrival we have opened a new research direction, *Extended Formulation Complexity.* We hope that Itai Arad will be able to integrate soon the group as the 5th PI. This would imply the opening of another research direction, *Hamiltonian Complexity* which is already present in the research agenda of several members of the group.

While Troy Lee's NRF Fellowship *Quantum query complexity, communication complexity, and semidefinite programming* is handled by NTU, there is a formal project agreement between NTU and CQT under which the research fellows employed by NTU on this grant are seconded to CQT.

II. GROUP MEMBERS AND VISITORS

A. Permanent group members

1. Principal Investigators: Rahul Jain, Hartmut Klauck, Troy Lee, Miklos Santha.
2. Senior Research Fellow: Itai Arad.
3. Research Fellows: Raghav Kulkarni, Youming Qiao, Jamie Sikora (since July 2014) Sarvagya Upadhya, Antonios Varvitsiotis, Zhaohui Wei, Penghui Yao (between December 2013 and July 2014)
4. Ph.D students: Anurag Anshu, Priyanka Mukhopadhyay, Attila Pereszlényi, Supartha Podder, Ved Prakash, Aarthi Sundaram, Penghui Yao (graduated in December 2013).

B. Visitors

1. Regular Visiting Researchers: Dmitry Gavinsky (three months per year), Gábor Ivanyos (three months per year), Iordanis Kerenidis (two months per year), Shengyu Zhang (two months per year).
2. Interns: Hardik Bansal, David Racicot-Desloges, Rohit Kumar, Biswaroop Maiti, Ankita Shukla.
3. Temporary visitors: Stacey Jeffery (IQC, Waterloo, 13 Oct 13 – 07 Nov 13 and 27 Apr 14 – 24 May 14), Matthew Mckague (University of Otago, 26 Nov 13 – 05 Dec 13), David Xiao (Princeton University, 29 Nov 13 – 29 Nov 13), Sadegh Raeisi (University of Waterloo, 07 Jan 14 – 01 May 14), Shima Bab Hadiashar (University of Waterloo, 16 Jan 14 – 26 Apr 14), Ala Shayeghi (University of Waterloo, 16 Jan 14 – 26 Apr 14), Adam Bouland (MIT, 17 Jan 14 – 11 Apr 14), Eunwoo Lee (South Korea, 17 Feb 14 – 19 Feb 14), Ariel Bendersky (ICFO Institut de Cincies Fotniques, 17 Mar 14 – 29 Mar 14), Tom Krenzke (31 Mar 14 – 06 Apr 14), Kaushik Chakraborty (Kolkata, 07 Apr 14 – 09 Apr 14), Priyaa Varshinee Srinivasan (University of Waterloo, 14 Apr 14 – 30 Apr 14), Michel de Rougemont (Universit Paris Diderot, France, 26 Apr 14 – 30 Apr 14) Jason Teutsch (Penn State University, 24 May 14 – 01 Jun 14).

III. RESEARCH HIGHLIGHTS

A. Algorithms and Complexity

1. In [18] we investigate the power of distributed networks made of quantum computers. We give tight lower bounds for a large number of graph problems, in particular giving the first lower bounds for the minimum spanning tree problem that are tight for all parameters, even for classical computation. [39] investigates the problem of computing the number of distinct elements in a datastream exactly, with the help of a powerful prover. We describe the first algorithm for which the number of interactions between the prover and the verifier is $O(\log n)$ and all other parameters are polylogarithmic.

2. In the theory of algebraic groups, parabolic subgroups form a crucial building block in the structural studies. In the case of general linear groups over a finite field $\mathbb{F}_q$, given a sequence of positive integers $n_1, \ldots, n_k$, where $n = n_1 + \cdots + n_k$, a parabolic subgroup of parameter $(n_1, \ldots, n_k)$ in $\mathrm{GL}_n(\mathbb{F}_q)$ is a conjugate of the subgroup consisting of block lower triangular matrices where the ith block is of size n_i. In [14] we give a polynomial time quantum algorithm in $\log q$ and n for solving the hidden subgroup problem in $\mathrm{GL}_n(\mathbb{F}_q)$, when the hidden subgroup is promised to be a parabolic subgroup. Our algorithm works with no prior knowledge of the parameter of the hidden parabolic subgroup. Prior to this work, such an efficient quantum algorithm was only known for minimal parabolic subgroups (Borel subgroups), for the case when q is not much smaller than n.

3. In [10], motivated by search for cryptosystems resisting quantum attacks, we study the quantum complexity of constructive subsemigroup membership in commutative semigroups, which is the following problem. Given elements $a_1, \ldots, a_k$ and b from a commutative semigroup of size N, express b as a product of powers of the a_is. The case $k = 1$ can be solved in time polynomial in $\log N$ using an extension of Shor's period finding method; while the case of $k \geq 2$ is difficult: in the black box model its quantum query complexity is $\Omega(N^{\frac{1}{2}-\frac{1}{2k}})$. This bound is essentially tight (for constant k): a combination of Grover's search over appropriate domains with Kuperberg's dihedral hidden subgroup algorithm, solves the problem in time $N^{\frac{1}{2}-\frac{1}{2k}+o(1)}$.

4. In [27] we study the finite group isomorphism problem when the groups are given by their Cayley tables. We advocate a strategy via the extension theory of groups, which describes how a normal subgroup N is related to G/N via G. This strategy "splits" GpI into two subproblems: one regarding group actions on other groups, and one regarding group cohomology. The solution of these problems is essentially necessary and sufficient to solve GpI. Most previous works on GpI naturally align with this strategy. We apply this strategy to solve GpI in $n^{O(\log \log n)}$ time for central-radical groups, and in polynomial time for several prominent subclasses of central-radical groups. To develop these algorithms we utilize several mathematical results on the detailed structure of cohomology classes, as well as algorithmic results for code equivalence and coset intersection.

5. In [31] we initiate a *systematic* study of constraint satisfaction problems in a trial and error model of computing, proposed in a recent work of Bei, Chen and Zhang (STOC 2013). In this model the input is hidden by an oracle which, for a candidate assignment, reveals some information about a violated constraint if the assignment is not satisfying. Based on a formal framework for CSPs, we define several types of revealing oracles. Our main contribution is to develop a *transfer theorem* for each type of the revealing oracle. To any hidden CSP with a specific type of revealing oracle, the transfer theorem associates another CSP in the normal setting, such that their complexities are polynomial time equivalent. This in principle transfers the study of a large class of hidden CSPs, possibly with a promise on the instances, to the study of CSPs in the normal setting. We show the power of the transfer theorems by applying them to various concrete CSP problem.

6. In [3] we studied the relations between global and energy distributions in general quantum spin systems on a lattice. These systems are characterized by a Hamiltonian that is made of nearest-neighbor interactions. Due to the non-commuting nature of the local interactions, eigenstates of the global Hamiltonian are not necessarily eigenstates of sub-Hamiltonians that are defined on a contiguous region on the grid. A simple Markovian argument, which does not utilize the full locality of the problem, gives a loose $1/poly(n)$ bound between these two distributions. Our result strengthen these to exponentially small bounds using roughly the same techniques that are used from proving the Lieb-Robinson bounds. These exponential bounds enable one to construct an approximation to the global Hamiltonian which (i) has a lower spectrum that is exponentially close to that of the original Hamiltonian, (ii) is completely local on a continuous region L on the grid, and (iii) has a *bounded, non-extensive norm.* A restricted form of this construction was used in the recent improvement of the 1D area-law.

7. In [11], we study dynamic complexity of some graph theoretic problems including reachability and matching. In this setting the edges of the graphs are added and deleted dynamically and we are interested in the complexity of the update/query in worst case. Immermann and Patnaik (1996) had conjectured that reachability between any two nodes in directed graphs can be maintained using so called first-order updates. This is a long-standing open question. We report two-fold progress: Firstly we explore the conjecture in "non-uniform" setting where the first order updates translate to having a constant depth circuit, i.e., being

in AC^0. We show that indeed there are polynomial size data structures that allow updates by polynomial size constant depth circuits if in addition to AND and OR gates, we allow parity gates. For matching we need to use threshold gates. Our main technique is the so called Isolation Lemma combined with a truncated rational approximations of polynomials over finite fields that builds on the previous work by Hesse. Secondly we confirm the Immermann and Patnaik's conjecture for the first non-trivial subclass of graphs, namely planar graphs. We use the duality between directed cuts and cycles for this purpose and develop many interesting structural lemmas on the way.

8. In [24] we make a natural step towards proving so-called KRW Composition Conjecture: if true, it would lead to a major breakthrough in our understanding of circuit complexity – one of the major open problems in complexity theory. While the original conjecture suggests that given two Boolean functions f and g, the depth complexity of the composed function $g \circ f$ is roughly the sum of the depth complexities of f and g, we show that an analogue of it holds for the composition of a function with a universal relation. We also suggest a candidate for the next step and provide initial results towards it. Besides, in this work, we develop general tools for analysing the information complexity of KW relations, which may be of independent interest.

B. Interactive Proofs, Zero Knowledge, Quantum Games

1. In our group we have been investigating *direct-sum* and *direct-product* questions in various models of computation, specially communication complexity, query complexity and multi-player games. These questions ask if saving of resources is possible when several instances have to be computed together. Direct-product (a.k.a. parallel repetition) question for classical two-payer games have been studied extensively culminating in the seminal result by Raz [1995]. This result along with the *PCP Theorem* has implied several in-approximability results. Recently there has been investigation of the same question for entangled two-player games. Dinur, Steurer and Vidick [2013] have shown a parallel repetition result for entangled *projection games* and Chailloux and Scarpa [2013] have shown a parallel repetition result for general entangled games when the questions to the players are drawn from uniform distribution. In [34], we show a parallel repetition result for general entangled games when the inputs for the two players are drawn from any product distribution. Our result improves upon the result of Chailloux and Scarpa [2013] and matches the parameters of Raz's result (for games under product distribution).

2. In a nonlocal game a verifier randomly chooses questions for players Alice and Bob. Without communicating, Alice and Bob respond by choosing one out of a set of possible outputs. To determine if the players win the game, the verifier evaluates a predicate that depends on the questions and their answers. We are interested in the setting where Alice and Bob share some entangled state that they use in order to determine their answers. An important open question is to understand how much entanglement is necessary so that the players can win the game with probability one. In [45] we show how one can associate a graph to any nonlocal game. Our main result there is that a nonlocal game has a perfect strategy using the maximally entangled stated iff the corresponding graph has a projective packing of value equal to the total number of questions.

3. Mochon's proof of existence of quantum weak coin flipping with arbitrarily small bias is a fundamental result in quantum cryptography, but at the same time one of the least understood. Though used several times as a black box in important follow-up results the result has not been peer-reviewed, its novel techniques (and in particular Kitaev's point game formalism) have not been applied anywhere else, and an explicit protocol is missing. We believe that truly understanding the existence proof and the novel techniques it relies on would constitute a major step in quantum information theory, leading to deeper understanding of entanglement and of quantum protocols in general. In [1], we make a first step in this direction. We simplify parts of Mochon's construction considerably, making about 20 pages of analysis in the original proof superfluous, clarifying some other parts of the proof on the way, and presenting the proof in a way which is conceptually easier to grasp. We believe the resulting proof of existence is easier to understand, more readable, and certainly verifiable. Moreover, we analyze the resources needed to achieve a bias ε and show that the number of qubits is $O(\log \frac{1}{\varepsilon})$, while the number of rounds is $\left(\frac{1}{\varepsilon}\right)^{O(\frac{1}{\varepsilon})}$.

C. Communication Complexity, Query Complexity and other aspects of Communication

1. The paper [38] gives the first example of a discrete problem, for which quantum proofs allow more efficient verification than classical proofs, even for quantum verifiers, i.e., a separation between QCMA- and QMA-type computation. Our separation is in the model of one-way communication complexity. In [21] the Equality problem is investigated in the model of 2-party simultaneous message passing, with and without an untrusted third party Merlin, who can see both inputs. We show the simplest proof yet of the $\Omega(\sqrt{n})$ lower bound for Equality in the randomized setting, extend the result to the case where one party can send a quantum message (yielding the first tight bound in this setting), and give tight lower and upper bounds for the setting involving a quantum or classical Merlin.

2. One important class of functions, XOR functions, has drawn an increasing amount of attention recently in studies of communication complexity. While there are lower bounds known for the quantum communication complexity of these functions, the tightness of the bound has been an intriguing open question. In a recent work [47] we gave a protocol with communication cost matching the lower bound for functions with low GF[2] degree d, a large class of functions with rich structures. This also confirms the quantum Log-rank Conjecture for low degree XOR functions.

D. Extended Formulation Complexity

1. Positive semidefinite rank (PSD-rank) is a newly defined quantity with applications to combinatorial optimization and communication complexity. Ruling out a certain approach to solving NP-hard problems efficiently via semidefinite programming requires showing lower bounds on the PSD-rank, and is currently a major open problem. Unfortunately, we currently have few techniques to lower bound the PSD-rank, and even its basic properties are not well understood. In the paper [44] we first address several properties of PSD-rank, including showing that the PSD-rank is not strictly multiplicative under tensor product, and that the real PSD-rank is at most a factor of 2 larger than the complex PSD-rank. Then we show several new lower bounds for PSD-rank. All of them depend on the values of the matrix and not only on its support structure, a limitation of some previous techniques. We also give nearly tight bounds on the PSD-rank of (approximations of) the identity matrix and on the PSD-rank of the matrix corresponding to the inner product and nonequality functions.

2. In the paper [36] we explore another approach to showing lower bounds on PSD-rank based on its characterization in terms of a model of quantum communication complexity. In this model the goal is to compute a function in expectation, that is output a random variable whose expectations is the desired function value, rather than with bounded error as in the usual model. In general, there is a close relationship between the query complexity of a function f and the communication complexity of the function $f(x \wedge y)$ and this connection also holds in the computing in expectation model. We define a function f such that showing lower bounds on the communication complexity of $f(x \wedge y)$ implies lower bounds on the size of SDP formulations for the traveling salesman problem. To give evidence that this is a good candidate function, we introduce a model of query complexity where the goal is compute a function in expectation and show that this f does require large quantum query complexity in this model.

IV. TEACHING AND OUTREACH

1. Rahul Jain course on *Advanced Algorithms* (CS 6234), NUS, Spring 2014.

2. Hartmut Klauck course on *Algorithms and Theory of Computing* (MAS714) NTU, Spring 2014.

3. Rahul Jain participated in the School of Computing booth at the NUS Open House 2014.

V. INVITED AND CONTRIBUTED TALKS

1. Dmitry Gavinsky contributed talks at *31st Symposium on Theoretical Aspects of Computer Science*, Lyon, France, March 2014, *41st International Colloquium on Automata, Languages*

and Programming, Copenhagen, Denmark, July 2014.

2. Gábor Ivanyos contributed talk at *Dagstuhl Seminar 13371 on Quantum Cryptanalysis*, Schloss Dagstuhl, Germany, September 2013; invited talk at *Algebra, Geometry and Computation 2014*, Eindhoven University of Technology, Eindhoven, Netherlands, July 2014.

3. Rahul Jain contributed talks at *13th Asian Quantum Information Science Conference*, Chennai, India, August 2013, *33rd Foundations of Software Technology and Theoretical Computer Science*, Guwahati, December 2013, *29th IEEE Conference on Computational Complexity*, Portland, US, June 2014.

4. Iordanis Kerenidis contributed talk at *FET OPEN QALGO* workshop, Brussels, May 2014.

5. Hartmut Klauck contributed talk at *Dagstuhl Seminar 14121 on Computational Complexity of Discrete Problems*, Schloss Dagstuhl, Germany, March 2014.

6. Troy Lee contributed talk at *Neural Information Processing Systems*, Lake Tahoe, US, December 2013.

7. Youming Qiao invited talk at *Arithmetic Circuit Complexity* workshop, Lyon, March 2014; contributed talks at *Dagstuhl Seminar 13371 on Quantum Cryptanalysis*, Schloss Dagstuhl, Germany, September 2013, *31st Symposium on TheoreticalAspects of ComputerScience*, Lyon, France, March 2014, *Conference on Groups, Computation and Geometries*, Colorado State University, US, June 2014.

8. Ved Prakash contributed talks at *SIGMOD Symposium on Principles of Database Systems PhD Symposium*, Snowbird, US, June 2014, *41st International Colloquium on Automata, Languages and Programming*, Copenhagen, Denmark, July 2014.

9. Miklos Santha invited talks at *New Mathematical Directions for Quantum Information* workshop, Newton Institute, Cambridge, September 2013, *Arithmetic Circuit Complexity* workshop, Lyon, March 2014, *Middlesex Algorithms Day*, Middlesex University, London, March 2014; contributed talks at *FET OPEN QALGO* workshop, Brussels, May 2014, *3rd French-Israeli FILOFOCS* workshop, Paris, May 2014.

10. Aarthi Sundaram contributed talk at *41st International Colloquium on Automata, Languages and Programming*, Copenhagen, Denmark, July 2014.

11. Shengyu Zhang contributed talks at *54th Annual IEEE Symposium on Foundations of Computer Science*, Berkeley, US, October, 2013, *25th Annual ACM-SIAM Symposium on Discrete Algorithms*, Portland, US, January, 2014, *17th Workshop Quantum Information and Processing*, Barcelona, Spain, February, 2014.

VI. CONFERENCE ATTENDANCE

1. Rahul Jain AQIS 2013, FSTTCS 2013, QIP 2014.
2. Iordanis Kerenidis TQC 2014.
3. Hartmut Klauck TQC 2014.
4. Troy Lee NIPS 2013, TQC 2014, STOC 2014.
5. Ved Prakash SIGMOD/PODS 2014, ICALP 2014.
6. Youming Qiao STACS 2014.
7. Miklos Santha STACS 2014.
8. Shengyu Zhang FOCS 2013, SODA 2014, QIP 2014.
9. Zhaohui Wei ISIT 2014.

VII. PROFESSIONAL ACTIVITIES

1. Gábor Ivanyos was on the PC of ISSAC 2014.
2. Rahul Jain was on the PC of TAMC 2013, ISAAC 2014, QIP 2014.
3. Iordanis Kerenidis was on the PC ICALP 2014. He is in the editorial board of *International Journal of Quantum Information.*
4. Hartmut Klauck was one of the local organizers of the 9th TQC, Singapore, May 2014.
5. Troy Lee was the main local organizer of 9th TQC Singapore, May 2014.
6. Miklos Santha is in the steering committee of FCT and in the editorial board of *International Journal of Quantum Information.*
7. Shengyu Zhang was on the PC of AQIS 2014. He is in the editorial board of *Theoretical Computer Science* and *International Journal of Quantum Information.*

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[1] D. Aharonov, A. Chailloux, M. Ganz, I. Kerenidis, and L. Magnin. A simpler proof of existence of quantum weak coin flipping with arbitrarily small bias. *ArXiv e-prints*, 2014.

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