Centre for Quantum Information and Communication
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Mémoires de Fin d'Etudes pour l'année académique 2019-20

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Thème général : Sciences de l'Information Quantique

Etudiants concernés : Ir. Physique ou Ms. Science Physique
Ir. Informatique ou Ms. Science Informatique

Pré-requis : Tous les sujets nécessitent des connaissances de base de mécanique quantique, de théorie des probabilités et d'algèbre linéaire.

Note : Certains sujets sont plus proches de la physique quantique (optique quantique, communication quantique, thermodynamique quantique), d'autres de l'informatique quantique (algorithmes quantiques, complexité quantique) ou bien encore des fondements de la physique quantique.

Langue : Français ou anglais en fonction de la personne qui supervise le mémoire (par souci d'uniformité, tous les sujets sont présentés en anglais ci-dessous)

1) Continuous majorization relations in quantum phase space

Supervisor: Nicolas Cerf

The theory of majorization provides a way of comparing probability distributions in terms of disorder. Whenever A majorizes B, it means that A is more ordered than B (consequently, A has a lower entropy than B). Majorization theory also turns out to have many applications in quantum information sciences, for example in relation with quantum entanglement or quantum channel capacity. This Ms thesis will investigate a much less explored continuous-variable counterpart of majorization theory and its role for comparing Wigner distributions in quantum phase space (*x,p*). We have good reasons to anticipate that it is a powerful tool in order to address a conjectured entropic uncertainty relations for position and momentum variables (namely, the vacuum state continuously majorizes all other quantum states with a positive Wigner function). In a second time, the objective of the Ms thesis would be to explore the possibility of extending the use of continuous-variable majorization relations to quantum states with non-positive Wigner functions (the Wigner function is a quasi-probability distribution, which is normalized as a genuine probability distribution but may admit negative regions in phase-space).

2) Photonic interference in linear optics circuits

Supervisor: Nicolas Cerf

Photonic quantum interference is a key resource for implementing future quantum technologies with photonic integrated devices, and in particular for so-called « boson sampling » devices. For this reason, there has recently been a regained interest in genuine multiphoton multimode quantum interference effects, going beyond the celebrated Hong-Ou-Mandel effect (an interferometric suppression effect that is due to the quantum indistinguishability of two photons : the trajectory where they are both reflected at a 50:50 beam splitter interferes destructively with the trajectory where they both cross the beam splitter). In interferometers with certain symmetries, multiphoton quantum interference effectively suppresses certain sets of detection events, which, mathematically, can be related to properties of the permanent of a matrix describing the interferometer. (NB : The permanent of a matrix is similar to its determinant but with all negative terms being turned into positive terms.) In this Ms thesis, we intend to identify such suppression effects in Fourier interferometers, which can be viewed as a multimode version of a 50:50 beam splitter. In a second time, the objective is to explore the extremality of Fourier interferometers among all multiport linear interferometers. More specifically, this would boil down to establish and attempt to prove the quantum counterpart of a central result on the permanent of doubly-stochastic matrices.

3) Entropic quantum uncertainty relations for more than two variables

Supervisor: Nicolas Cerf

While they were originally formulated in terms of variances, quantum uncertainty relations have later been expressed with entropies, following the advent of Shannon information theory. In this context, a famous entropic uncertainty relation, due to Bialynicki-Birula and Mycielski in 1975, connects the entropy of two canonically-conjugate continuous variables, such as position and momentum. It states that the sum of their Shannon entropies cannot be lower than a certain constant, depending on Planck constant h. This continuous-variable uncertainty relations has been generalized in various directions, for example when considering arbitrary (not necessarily canonically-conjugate) variables, but little is known to the case where more than two continuous variables are considered. The objective of this Ms thesis is to explore the construction of entropic uncertainty relations involving N variables. A famous uncertainty relations for N variables had been derived by Robertson in 1934, but it is based on the covariance matrix of the measured observables (it states that the covariance matrix is larger than some commutator matrix). Its possible entropic version has only been recently formulated by QuIC researchers but much work remains to be done in order to confirm it. In this Ms thesis, some special cases will be considered as well as the question of whether Gaussian pure states are minimum uncertainty states. The formulation of these continuous-variable uncertainty relations in terms of entropy power, a central quantity in the information-theoretic description of random signals, will also be exploited.

4) Resource theory of non-passivity in quantum thermodynamics
Supervisor: Nicolas Cerf

Thermodynamics is a macroscopic theory applicable in the limit where the number of particles and volume tend to infinity. However, with our increasing ability to control and manipulate small systems, such as the realization of molecular motors and nanomachines, the scope of applicability of thermodynamics is starting to stretch beyond the macroscopic region. One of the main goals of the thermodynamics of small systems – a new field called quantum thermodynamics – is the extraction of work by means of cyclic Hamiltonian transformations of a quantum state. Quantum thermodynamics can be cast as a « resource theory » by viewing the Gibbs state (thermal state) as a state that is « free » and hence any other state as a resource for work extraction. The notion of passive state generalizes the notion of thermal state in quantum thermodynamics : it is a state from which no work can be extracted by means of any unitary operator applied to the quantum system. The objective of this Ms thesis is to pursue a current research project at QuIC, where the non-passivity of a state (the ability to extract work) is treated as a « resource ». A resource theory of non-passivity and so-called resource monotones could be built based on this idea. Alternatively, other sets of free states could be explored in this context, such as states with a thermodynamically relevant symmetry (e.g., states that are invariant under any energy-preserving unitary). To be more specific, this study could possibly be restricted to bosonic systems (a set of harmonic oscillators).

5) Adiabatic quantum computing via Markovian dynamics
Supervisors: Jérémie Roland & Ognyan Oreshkov

Quantum computers promise to solve certain problems more efficiently than classical computers. The standard model of quantum computation works by applying a sequence of quantum gates (or unitary operations) on a set of qubits. An alternative model, which is equivalent in computational power, is Adiabatic Quantum Computing. In this model, the quantum computer is initially prepared in the ground state of a specific Hamiltonian, and the computation works by slowly turning off this Hamiltonian while at the same time turning on another one whose ground state encodes the solution of the computational problem. If this interpolation is performed slowly enough, the quantum adiabatic theorem guarantees that the initial ground state will be transformed into the final ground state.

Recently, the adiabatic theorem was extended from the case of closed quantum system undergoing Hamiltonian dynamics to the case of open quantum systems undergoing dissipative Markovian dynamics, and it was shown that this more general type of adiabatic dynamics can be used to perform various tasks. This project will explore the possibility to perform adiabatic quantum computation via adiabatic Markovian dynamics.

6) Applications of the quantum linear systems algorithm
Supervisor: Jérémie Roland

Algorithms to solve linear systems find applications in a wide range of fields. Quantum algorithms for solving linear systems outperform its classical counterpart and in some regimes, fare exponentially better. This project would aim at exploring the applications of this quantum algorithm to various problems and also at techniques that help in extracting useful information from its output. This would also involve analyzing existing techniques by which quantum computers can simulate quantum systems faster than any classical computer. Successful completion of this project will lead to improving existing quantum algorithms for data-fitting and to better quantum algorithms for estimating the time required by a quantum walker to hit a given set of vertices in a graph.

7) Simulation of imperfections on photonic near-term quantum computers
Supervisor: Dr. Raul Garcia-Patron Sanchez (Chercheur qualifié FNRS)

While there is still a long road before we build a quantum computer, established companies, such as Google or IBM, together with new born startups will build within the next few years quantum devices which are sufficiently large that they cannot be simulated with our best digital supercomputers. This intermediate-scale quantum technology will be noisy but will have the potential to run quantum simulations and algorithms that could outperform classical computers for specific targeted applications and explore new physics. Understanding how noise affect these devices and their computational advantage over classical computers is an open question of high relevance for the development of this early stage technologies.

In the last couple of years, we have developed at ULB a series of classical algorithms that simulate imperfect near-term photonic quantum computing devices suffering from losses and distinguishability of photons. This sheds light on the quantum-to-classical transition of such devices.

In this project, we propose to extend our current algorithms to include all the most relevant imperfections of a photonic quantum computing platform. The project is of a theoretical nature, as we will focus on the design of the algorithm, a theoretical/mathematical task.

Student required background: A physics student or a computer science student with interest in physics and eager to learn quantum computation.

8) Numerical study of effects of imperfections on photonic near-term quantum computers
Supervisor: Dr. Raul Garcia-Patron Sanchez (Chercheur qualifié FNRS)

While there is still a long road before we build a quantum computer, established companies, such as Google or IBM, together with new born startups will build within the next few years quantum devices which are sufficiently large that they cannot be simulated with our best digital supercomputers. This intermediate-scale quantum technology will be noisy but will have the potential to run quantum simulations and algorithms that could outperform classical computers for specific targeted applications and explore new physics. Understanding how noise affect these devices and their computational advantage over classical computers is an open question of high relevance for the development of this early stage technologies.

In the last couple of years, we have developed at ULB a series of classical algorithms that simulate imperfect near-term photonic quantum devices suffering from losses and distinguishability of photons. This seeds light on the quantum-to-classical transition of such devices.

In this project we propose to translate those algorithms into efficient code that can be used to simulate large-size quantum computing photonic devices under imperfections, and we will experientially test its performance against real scenarios.

Student required background: A physics student that likes writing code and running numerical simulations or a computer science student with interest in physics and eager to learn quantum computation.

9) Simulation of imperfections on fermionic near-term quantum computers
Supervisor: Dr. Raul Garcia-Patron Sanchez (Chercheur qualifié FNRS)

While there is still a long road before we build a quantum computer, established companies, such as Google or IBM, together with new born startups will build within the next few years quantum devices which are sufficiently large that they cannot be simulated with our best digital supercomputers. This intermediate-scale quantum technology will be noisy but will have the potential to run quantum simulations and algorithms that could outperform classical computers for specific targeted applications and explore new physics. Understanding how noise affect these devices and their computational advantage over classical computers is an open question of high relevance for the development of this early stage technologies.

In the last couple of years, we have developed at ULB a series of classical algorithms that simulate imperfect near-term photonic quantum devices suffering from losses and distinguishability of photons. This seeds light on the quantum-to-classical transition of such devices.

In this project we propose to adapt our current algorithms that work for bosonic particles to fermionic particles in order to investigate the similarities and differences between both families of particles and conjecture potential universal behaviors for all large-size quantum devices. The project is of theoretical nature, as we will focus on the design of the algorithm.

Student required background: A physics student or a computer science student with interest in physics and eager to learn quantum computation.

10) Processes with indefinite causal structure in quantum theory
Supervisor: Ognyan Oreshkov

It was recently found that quantum theory permits higher-order processes in which the order of the operations performed by separate parties is not definite, similarly to the way the position or momentum of a quantum particle may be indefinite. This Ms thesis will explore the possibility of realizing this phenomenon in practice, as well as the novel information-processing capabilities it allows.

11) New symmetry transformations through post-selection
Supervisor: Ognyan Oreshkov

The concept of symmetry is fundamental for our understanding of the laws of physics. It was recently shown that reconciling the probabilistic laws of quantum theory with the requirement for time-reversal symmetry requires a generalized formulation of quantum theory, which implies the possibility for more general symmetry transformations than those previously believed possible. This Ms thesis will explore the possibility of realizing this new type of symmetry transformations through post-selection.