

Master's Research Projects in Quantum Computing

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From February 2027, I will be a permanent CNRS researcher in the QAT (Quantum computing: Architectures, Algorithms, Applications and their Theory, qat.inria.fr) team at DIENS, École Normale Supérieure – PSL. I am happy to supervise Master's internships and Master's theses in quantum computing and quantum information.

A recurring question in my research is:

Where is the boundary between quantum computations that can outperform classical methods and those that can be efficiently simulated classically?

A generic quantum state requires exponentially many parameters to describe. However, in many applications, we do not need a complete description of the state: we may only want to predict a few observables, reproduce certain measurement statistics, or solve a specific computational task. My research studies when simple, effective descriptions of a quantum system are possible, and how they can be exploited algorithmically. This naturally connects classical simulation, quantum learning theory, the analysis of noisy quantum devices, and hybrid classical–quantum algorithms.

Projects can be predominantly analytical or numerical, depending on the student's interests and background.

Below is a **non-exhaustive** list of potential topics. If you would like to discuss one of these directions, or a related project, feel free to contact me by email with a short description of your background and research interests.

Learning and simulating continuous-time quantum dynamics

Quantum computations are usually represented as sequences of discrete quantum gates. Physical quantum systems, however, evolve continuously in time. Understanding continuous-time dynamics is therefore important both as a model of quantum computation and as a description of actual experiments.

Recent work has shown that surprisingly complex quantum dynamics can sometimes be predicted without reconstructing the entire quantum process. Huang, Chen and Preskill [1], for example, developed learning methods for predicting properties of general quantum processes. In a complementary direction, Angrisani *et al.* [2] showed that observables of broad families of noiseless quantum circuits can be estimated efficiently using *Pauli propagation*, a framework for classically simulating quantum systems by propagating observables rather than full quantum states [3].

Pauli propagation works in the Heisenberg picture: instead of simulating the full quantum state as it passes through a circuit, one propagates the observable of interest backwards through the computation and represents it in the basis of Pauli operators. In certain regimes, the observable can be approximated with few Pauli operators even though the complete state is highly complicated. A natural question is whether similar phenomena occur for continuous-time quantum processes. Interesting examples include Brownian quantum dynamics, where the Hamiltonian itself fluctuates randomly in time [4], and more general random processes with temporal correlations that decay over time.

Possible projects will investigate when such dynamics admit compact classical representations that can be efficiently learned or simulated, and how the answer depends on evolution time, locality, mixing and temporal correlations.

Classical simulation under correlated quantum noise

Noise is one of the principal limitations of current quantum hardware, and a significant obstacle to achieving quantum computational speedups. In particular, sufficiently noisy quantum computations may become much easier to simulate classically.

A series of recent results has established efficient classical simulation in different noisy regimes [5, 6, 7]. In particular, our work on Pauli propagation shows that typical circuits affected by very general forms of *local* noise admit efficient classical estimation of observables [7].

An important limitation of current rigorous simulation guarantees is that they largely assume noise that is sufficiently local and not correlated. Real devices can instead exhibit errors correlated across several qubits and over multiple timescales. For example, correlated charge fluctuations have been observed in superconducting quantum processors [8].

This motivates a basic question:

When does spatially and temporally correlated noise still simplify a quantum computation enough to make it classically predictable?

Projects in this direction will develop models and simulation methods for correlated noise and study the transition between regimes that remain classically tractable and those in which correlations preserve complex quantum behaviour. Pauli propagation provides one natural framework for this question [3], although alternative methods may also be appropriate.

Quantum resources under physical constraints

One way of understanding quantum computational power is through *resource theories*. A resource theory starts by specifying a set of states and operations that are regarded as “free”—for example because they are easy to prepare, manipulate, or simulate—and asks what additional resources are needed to perform more general tasks.

Entanglement [9] and magic [10] are two famous examples. Their presence can allow a quantum system to reach states or observables that would otherwise be inaccessible, and they are closely connected to the classical complexity of quantum computations.

Most such notions of complexity are considered without imposing additional physical restrictions on the dynamics. However, real physical evolution is often constrained by conservation laws. A paradigmatic example is provided by thermal operations [11], which are built from energy-preserving dynamics. If an evolution must preserve energy, it cannot explore the entire Hilbert space, since the dynamics is restricted by the underlying energy structure.

This raises a conceptual question:

How should quantum complexity and quantum resources be defined when physical conservation laws restrict the portion of state or operator space that can actually be explored?

We will investigate notions of *operator complexity* adapted to such constrained dynamics, and study how they evolve in random circuits and other analytically or numerically tractable models.

Hybrid classical-quantum algorithms

The boundary between classical and quantum computation need not be all-or-nothing. A quantum device can be used selectively, providing pieces of information that are hard to compute classically and that can then be stored, propagated, and reused by a classical algorithm.

Our recent work gives one example: quantum measurements can be used to build classical surrogates of expectation-value landscapes [12]. This suggests a broader class of *quantum-enhanced*

propagation algorithms, in which a compact classical representation carries most of the computation, while the quantum device is invoked only when genuinely hard-to-compute information is needed.

A central question is how to allocate a limited quantum budget. Is it better to obtain many noisy quantum samples, or fewer high-quality—possibly error-corrected—ones? How should quantum circuit depth, measurement cost, classical runtime, and target accuracy be traded against one another?

Projects in this direction will develop and analyse hybrid algorithms that combine limited quantum access with classical simulation. One concrete goal is to develop resource-efficient variants of quantum optimization algorithms such as QAOA [13], where repeated shallow quantum circuits are combined with classical propagation and post-processing. The aim is to understand whether this hybrid strategy can reproduce useful features of computations that would otherwise require substantially greater quantum depth.

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