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Quantum simulation and control with Qibo

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We present Qibo, an open-source framework for fast evaluation of quantum circuits and adiabatic evolution which takes full advantage of hardware accelerators, quantum hardware calibration and control. The growing interest in quantum computing and the recent developments of quantum hardware devices motivates the development of new advanced computational tools focused on performance and usage simplicity. In this work we introduce a new quantum simulation framework that enables developers to delegate all complicated aspects of hardware or platform implementation to the library so they can focus on the problem and quantum algorithms at hand.

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Holographic Realization of the Prime Number Quantum Potential

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We report the experimental realization of the prime number quantum potential $V_N(x)$, defined as the potential entering the single-particle Schroedinger Hamiltonian with eigenvalues given by the first N prime numbers. Using computer-generated holography, we create light intensity profiles suitable to optically trap ultracold atoms in these potentials for different N values. As a further application, we also implement a potential whose spectrum is given by the lucky numbers, a sequence of integers generated by a different sieve than the familiar Eratosthenes's sieve used for the primes. Our results pave the way towards the realization of quantum potentials with arbitrary sequences of integers as energy levels and show, in perspective, the possibility to set up quantum systems for arithmetic manipulations or mathematical tests involving prime numbers, including the factorisation of integers, essentially for quantum cryptography.

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Opening the black box of quantum machine learning

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I will discuss different theoretical results on using quantum computers for learning classical data, and on the use of classical and quantum computers to learn quantum states, quantum processes and quantum channels. In particular, I'll focus on foundational aspects, by introducing entropic measures that allow us to identify what kind of problems can be easily learnt directly from the data.

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Evaluation quantum gradient through quantum non-demolition measurements

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Even if error-free quantum computers are still decades away, today's generation of quantum computers should be able to attack classically unsolvable computational problems.
The paradigmatic example is the search for the energy minimum of medium size quantum systems.
These problems are usually classified as variational quantum algorithms and require a hybrid quantum-classical computer architecture.
While quantum computers allow us to estimate the energy of the quantum system, the classical counterpart uses a classical algorithm (such as the gradient-descendent algorithm) to drive toward the desired minimum.
In this context, it is of crucial importance the estimation the derivatives of the energy as a function of the controllable system parameters.

Quantum mechanics allows for a different way to extract information: strong projective measurements, weak measurements, non-demolition measurements and so on.
I will present a novel approach based on the non-demolition measurement that aims to simplify this process of the estimation of the derivative of the energy by introducing a quantum detector.
The information about the energy gradient is stored in the detector phase that is eventually measured.

This allows us to directly estimate the derivatives of the energy and consistently reduce the resources needed to run the variational quantum circuits.
I will discuss several advantages that this approach has with respect to the standard direct measurement approach.

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Trapped-Ion Quantum Simulation of Collective Neutrino Oscillations

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Studies of neutrinos from astrophysical environments such as core-collapse supernovae, neutron star mergers and the early universe provide a large amount of information about various phenomena occurring in them. The description of the flavor oscillation is a crucial aspect for such studies, since the physics of matter under extreme conditions is strongly flavor-dependents (nucleosynthesis, proton/neutron ratio, spectral splits...).
It is well known that the neutrino flavor changes under the effect of 3 contributions: the vacuum oscillation, the interaction with the electrons of the surrounding matter, and the collective oscillations due to interactions between different neutrinos.
This last effect adds a non-linear contribution to the equations of motion, making the exact simulation of such a system inaccessible from any current classical computational resource.

Our goal is to describe the real time evolution of a system of many neutrinos by implementing the unitary propagator $U(t) = e^{-iHt}$ using quantum computation and paying attention to the fact that the flavor Hamiltonian H, in the presence of neutrino-neutrino term, presents an all-to-all interaction that makes the implementation of $U(t)$, into a quantum algorithm, strongly dependent on the qubit topology/connectivity.

In this contribution we present an efficient way to simulate the coherent collective oscillations of a system of N neutrinos motivating the benefits of full-qubit connectivity which allows for more freedom in gate decomposition and a smaller number of quantum gates making simulation on near-term quantum devises more feasible.

We present the results obtained from a real quantum simulation on a trapped-ions based quantum machine for the cases of $N = 4$ and $N = 8$ neutrinos.

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Metodi Tensor Networks per teorie di gauge su reticolo

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Le teorie di gauge rivestono un ruolo fondamentale nella nostra comprensione dei costituenti fondamentali della materia e delle loro interazioni, dalla fisica delle alte-energie alla fisica quantistica

a molti corpi a bassa temperatura. Tuttavia, la caratterizzazione completa dei loro diagrammi di fase e la piena comprensione degli effetti non-perturbativi sono ancora dibattuti, specialmente nei regimi di densità di carica finita, principalmente a causa del problema del segno che interessa le simulazioni numeriche Monte Carlo. Negli ultimi anni, un approccio numerico complementare basato sulle Tensor Networks (TN), in stretta connessione con i paradigmi dell'informazione quantistica e delle tecnologie quantistiche emergenti, ha trovato applicazioni crescenti per lo studio delle teorie di gauge su reticolo nei sistemi a bassa dimensionalità. In questo intervento, presenterò alcuni risultati recenti riguardanti l'estensione degli algoritmi TN a teorie di gauge in alta dimensionalità. In particolare, mi concentrerò sulla loro applicazione all'elettrodinamica quantistica su reticolo, affrontando questioni come la caratterizzazione delle fasi collettive del modello, la presenza di fasi confinanti e lo studio di effetti di screening.

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A generalized eigenvalue problem via a quantum annealer

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As is well-known, eigenvalue problems have to be solved in many areas of physics and applied sciences. While several algorithms exist for classical computing, the possibilities of quantum computing in this field are not entirely explored. In this talk, we will present a quantum annealer algorithm based on the D-wave system that has the aim of solving the Generalized Eigenvalue Problem for the Symmetric and for the first time (to our knowledge) the Non-symmetric case. As an example, we will present an application of this algorithm to the homogeneous Bethe-Salpeter equation, that allows to non-perturbatively describe the dynamics in a bound system, within the relativistic quantum-field theory. The algorithm has been developed in the context of an approved project of Q@TN.

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Control Optimization for Parametric Hamiltonians by Pulse Reconstruction

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Optimal control techniques provide a means to tailor the control pulse sequence necessary for the generation of customized quantum gates, which help enhancing the resilience of quantum simulations to gate errors and device noise. However, the substantial amount of (classical) computing required for the generation of customized gates can quickly spoil the effectiveness of such an approach, especially when the pulse optimization needs to be iterated. We present the results of device-level

quantum simulations of the unitary (real) time evolution of two neutrons interacting, based on superconducting qudit, and propose a method to reduce the computing time required for the generation of the control pulses for the neutrons interaction Hamiltonian depending parametrically on the time-varying relative position of the two particle. We use a simple interpolation schemes to accurately reconstruct the control pulses sequence starting from a set of pulses obtained for a discrete set of predetermined neutrons relative positions. The reconstruction so obtained achieves very high fidelity and a substantial reduction of the computational effort.

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Long-lived particle Anomaly detection with parameterized quantum circuits

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We present a study on the possibility to apply quantum machine learning techniques for the detection of anomalous patterns in a typical high energy physics detector. To approach this task we propose an anomaly detection algorithm based on a parameterized quantum circuit. The algorithm has been trained on a classical computer and tested with simulations as well as on real quantum hardware. Tests on NISQ devices have been performed with IBM quantum computers. For the execution on quantum hardware some hardware driven adaptations have been implemented. The quantum anomaly detection algorithm is able to detect simple anomalies like different characters in handwritten digits as well as more complex structures, like anomalies in the particle distributions due to displaced tracks inside a typical muon detector at a collider experiment. For this latter case, while we prove that it is possible to perform anomaly detection with a quantum algorithm, the required quantum circuit is not simple enough to be executed with the quantum hardware that was available for the study. In particular we show that, due to the necessary amplitude encoding of classical data, the quantum algorithm is not able to outperform classic anomaly detection algorithms on the available quantum hardware.

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Ab-initio two-dimensional digital twin for quantum computer benchmarking

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Nell'era dei 'Noisy Intermediate Scale Quantum' (NISQ) computer, simulare la dinamica di circuiti quantistici con un elevato numero di qubits a livello dell'Hamiltoniana può essere rilevante per lo sviluppo di strategie efficienti e scalabili per implementare algoritmi in specifici hardware quantistici. Tramite l'impiego di sofisticati metodi di tensor networks, abbiamo sviluppato un 'digital-twin' di un computer quantistico ad atomi di Rydberg dimostrando il potenziale di tali simulazioni classiche per supportare lo sviluppo di hardware sia esistenti che futuri. Ad esempio, abbiamo quantificato l'effetto di crosstalks tra gate quantistici indotto dalla forte interazione di Van der Waals tra atomi di Rydberg,

per valutare la possibilità di eseguire gate quantistici in parallelo in tale piattaforma. Effettuando una simulazione di una griglia 8x8 di atomi, basata sullo stato dell'arte di setup sperimentali, abbiamo dimostrato che uno stato Greenberger-Horne-Zeilinger (GHZ) di 64 qubits può essere implementato eseguendo gate quantistici in parallelo con una fidelity elevata e con uno speedup del 35% rispetto all'esecuzione seriale dell'algoritmo.

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Entanglement entropy production in Quantum Neural Networks

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Le Reti Neurali Quantitiche (RNQ) sono candidate al raggiungimento del vantaggio quantistico nell'era dei Noisy Intermediate Scale Quantum (NISQ)computers. Diverse architetture di RNQ sono state proposte e testate con successo su dataset di prova utilizzati nel machine learning. Tuttavia, l'entanglement generato dalle RNQ non è stato studiato in maniera quantitativa per RNQ con più di pochi qubits. I metodi di tensor network permettono di simulare circuiti a molti qubit in molti scenari. In questo lavoro, impieghiamo i matrix product states (MPS) per caratterizzare architetture di RNQ recentemente studiate contenenti fino a cinquanta qubits. Mostriamo che l'entropia dell'entanglement generato tende a quella dello stato random uniformemente distribuito di Haar quando la profondità della RNQ aumenta. Osserviamo un comportamento universale dell'entanglement prodotto una volta fissata l'architettura, e quindi introduciamo una nuova misura per caratterizzare la produzione di entanglement nelle RNQ, detta entangling speed. Infine, in accordo con i risultati presenti in letteratura, discutiamo che il regime più promettente per raggiungere il vantaggio quantistico usando RNQ sia definito da un bilanciamento tra entangling speed ed expressibility.

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Quantum machine learning for jet classification at LHCb

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Machine Learning algorithms are playing a fundamental role in solving High Energy Physics tasks. In particular, the classification of hadronic jets at the Large Hadron Collider is suited for such types of algorithms, and despite the great effort that has been put in place to tackle such a classification task, there is room for improvement. In this context, Quantum Machine Learning is a new methodology that takes advantage of the intrinsic properties of quantum computation (e.g. entanglement between qubits) to possibly improve the performance of a classification task. In this contribution, a study of Quantum Machine Learning applied to jet identification is presented. Namely, a Variational Quantum Classifier is trained and evaluated on fully simulated data of the LHCb experiment. The jet identification performance of the quantum classifier is compared with a Deep Neural Network using the same input features. The performance of the algorithm measured on quantum hardware will be also discussed.

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IBM quantum platforms: a quantum battery perspective

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We characterize for the first time the performances of IBM quantum chips as quantum batteries, specifically addressing the single-qubit Armonk processor. By exploiting the Pulse access enabled to some of the IBM Quantum processors via the Qiskit package, we investigate advantages and limitations of different profiles for classical drives used to charge these miniaturized batteries, establishing the optimal compromise between charging time and stored energy. Moreover, we consider the role played by various possible initial conditions on the functioning of the quantum batteries. As main result of our analysis, we observe that unavoidable errors occurring in the initialization phase of the qubit, which can be detrimental for quantum computing applications, only marginally affects energy transfer and storage. This can lead counter-intuitively to improvements of the performances. This is a strong indication of the fact that IBM quantum devices are already in the proper range of parameters to be considered as good and stable quantum batteries, comparable to state of the art devices recently discussed in literature.

G. Gemme, M. Grossi, D. Ferraro, S. Vallecorsa, M. Sassetti, Batteries 8, 43 (2022)

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Use of a Quantum Annealer in optimization problems

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Quantum computing is becoming a new paradigm in computational physics, with two complementary emerging approaches, the circuit-based technology and the quantum annealers such as D-Wave. To better understand the software and the hardware performances of these new technologies, we have started to investigate how to solve a general optimization problem with the Quantum Annealer D-Wave thanks to a 2021 grant by Q@TN (Quantum Science and Technology in Trento) for Access to the CINECA Quantum Computing facility. As a first use case, we have selected the physics of phase transitions in two systems: the well known Frustrated Ising Model \[1\] and the more challenging Graphene honeycomb lattice \[2\]. The solution of these problems, presented in this work, open the possibility to master these new computing techniques and to extended them to other problems of interest for the INFN community. The Quantum Annealer can be exploited for particles and nuclear physics problems and in principle for any minimization task, both in fundamental and applied studies.

The Ising model with nearest-neighbor interactions on the two-dimensional (2D) square lattice is the simplest model to study the ferromagnetic to paramagnetic transition. On the D-Wave, we have implemented a more complex Ising model with the addition of competing antiferromagnetic interactions between the diagonal neighbors with two coupling constants J_1 and J_2. With this configuration, the Hamiltonian is represented as a graph which is embedded into the D-Wave hardware topology with a given connectivity degree. This embedding is crucial since the D-Wave topology is different from the topology of the starting graph: moreover each calculation is performed with different connections among the qubits and gives a slightly different result. We study the behaviour of the solution with different annealing parameters, such as the chain strength and the annealing time. The magnetization plot in Fig. 1 is promising, since we can identify the phase transition by varying the ratio between the ferromagnetic and antiferromagnetic couplings.

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Fig. 1 caption: Magnetization transition phase. The plot shows a conventional behavior when a material has a transition phase. Near the transition point, the lattice reaches its maximum complexity, and the error associated with the measure increases in value. The quantum annealing simulations are performed on two dimensional square lattice with L=20x20.

We propose to apply the same technique to study the magnetism of Graphene with a Hubbard-like Hamiltonian: the mapping of such a complex Hamiltonian to an Ising form is a new, emerging and not trivial activity. First results have been obtained for simple molecules \[3\] by rewriting the second quantization Hamiltonian in terms of Pauli spin matrices: this technique, that relies on the use of ancillary qubits in addition to the original lattice, has been recently proposed for a Fermi-Hubbard problem \[4\]. The use of a Quantum Annealer to explore the unique properties of Graphene could also speed up the theoretical investigation of the properties of this material for innovative sensors and detectors \[5\].

\[1\] Park & Lee, *Phase transition of Frustrated Ising model via D-wave Quantum Annealing Machine*, arXiv:2110.05124v1 (2021)

\[2\] S. Pezzini, C. Cobaleda, B.A. Piot, V. Bellani & E. Diez, *Critical point for the canted antiferromagnetic to ferromagnetic phase transition at charge neutrality in bilayer graphene*, Phys. Rev. B 90,121404 (2014)

\[3\] R. Xia et al., *Electronic structure calculations and the Ising hamiltonian,* The Journal of Physical Chemistry B 122 (2017) 3384

\[4\] R. Levy et al., *Towards solving the Fermi-Hubbard model via tailored quantum annealers*, arXiv:2207.14374v1.

\[5\] Shang-Yung Wang, *Graphene-based detectors for directional dark matter detection*, arxiv:1509.08801v3 (2019).

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A Containerized Quantum Application Software Architecture Framework

Autore: Antonello Aita[1]; Federico Accetta[1]; Federico Mattei[1]; Giacomo Bartoli[1]; Luca Crippa[2]; Michele Grossi[3]; Vito Sammarco[1]

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Starting from the idea of Quantum Computing, conceptualized back to 80s, we come to the present day being able to perform calculations on real prototype quantum computers. Recent technology improvements open new scenarios that quickly lead to the real possibility to integrate this technology into current software architectures. Designing a software on distributed systems is based on essential pillars, such as modularity, openness, and reuse of components. Typically, an application is divided into logical layers allowing targeted interventions on decoupled elements; however, exploiting frameworks that allow computation to be performed on a hybrid classical-quantum backend poses a series of challenges. We present here a scalable and open software architecture that can be reused as a design pattern whenever dealing with similar problems, being able to receive requests from the user, send them to a quantum computer and receive back the result by assuring the ordering and coherence of events as well as the right format; moreover, the aim of the proposed architecture is to bridge the gap between the classical and quantum computation for real problems.
As quantum technology development will continue to reach significant milestones, enterprises and researchers will be likely to use on a daily basis in the near future: an Enterprise would indeed be oriented to a progressive integration of quantum computing in their production architectures, to support and improve existing workloads.
A first attempt to develop a proprietary basilar framework has been proposed in this blog and in this article by the authors of this document, and has been published as disclosure. Now we improved the previous version by creating a new framework leveraging on an Enterprise Cloud technology such as Red Hat OpenShift, to achieve best portability and to exploit the extended number of services that this solution has to offer in terms of data storage, hosting, middleware, and message queue services.
A real implementation of this framework has been put in place as a Minimum Viable Product, that can be downloaded from a public GitHub repository.

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1 Build and deploy Quantum-based web Applications using Qiskit & Python Flask on IBM Cloud, M. Grossi, A. Aita, L. Crippa, 2019, Medium
[2] A Serverless Cloud Integration For Quantum Computing, M. Grossi, L. Crippa, A. Aita, G. Bartoli, V. Sammarco, E. Picca, N. Said, F. Tramonto, F. Mattei
[3] Method and system to create and deploy Cloud containerized quantum-based web applications using API-exposed quantum computers as back-end, 2019, IPCOM000258553D, Prior Art Database

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Quantum-notebook: a Docker stack for quantum computing

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Activities on Quantum computing are increasing thanks to the push of large investments promoted by Governments, Industries, and international actors of research. This environment stimulates the creation and integration of tools and components to design and simulate quantum circuits.
At the current state of the art, there are several different languages and frameworks for programming quantum computers, among them some of the most famous are Qiskit, Cirq, QASM, Q# and others.

In this work is presented a Quantum-Notebook built as a ready-to-deploy Docker image, based on JupyterHub technologies which implements a set of largely used tools for simulation or quantum programming.

Built on top of Jupiter Docker stack, the Quantum-Notebook provides a ready to use web-app to start directly programming in the preferred language, simplifying the installation steps. The image can be pulled and run on any device, such a laptop, server, or a cloud VM thanks to the versatility of docker.
Finally the Quantum-Notebook is easy to extend with additional libraries and is reusable in different contexts for development, simulation or training sessions.

The goal of this work is to give a contribution for helping, researchers, students, teachers and interested people to approach quantum programming.

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Quantum Technologies nel PNRR

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Quantum Machine Learning: from theory to practice @ CERN

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Metodi di quantum computing per tracciamento di particelle cariche

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Quantum Fuzzy Inference in Particle Accelerator Control

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Fuzzy Logic is a theory which can model classes of objects that do not have precisely defined criteria of membership in a way to mimic human thinking. Thanks to this capability, fuzzy logic has found great application in the field of automatic control and decision making, explained by the fact that expert knowledge is easily introduced into fuzzy systems, by means of fuzzy rules. Despite their success, fuzzy rule-based systems (FRBSs) suffer from the fuzzy rule explosion problem: the number of rules in a FRBS grows exponentially with the number of variables that makes up the system, limiting the possibility of controlling environments characterized by a high number of variables.
A recently proposed Quantum Fuzzy Inference Engine (QFIE) solves this problem thanks the parallelism provided by quantum computers. Indeed, it has been proved that by formalizing a FRBS as a Boolean oracle, QFIE requires exponentially fewer queries to the oracle than its classical counterpart.

This talk aims to introduce the peculiarities of QIFE and to show the results obtained in the experimentation carried out at the European Organisation for Nuclear Research (CERN), where QFIE has been tested in controlling particle accelerator beam lines. The results obtained have shown the capability of such a quantum control system in controlling these complex environments.

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Bayesian Optimization for QAOA

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We present a Bayesian optimization procedure to fulfil this optimization task of the QAOA algorithm, and we investigate its performance in comparison with other global optimizers. Our approach allows for a significant reduction in the number of calls to the quantum circuit, which is typically the most expensive part. We demonstrate that our method works well also in the regime of slow circuit repetition rates, and that few measurements of the quantum ansatz would already suffice to achieve a good estimate of the energy.

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Noise gates for quantum computing

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Noisy Gates for Quantum Computing

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Assessing the effect of noises in quantum computers is a major task for understanding their practical applicability for solving real-life problems. In quantum mechanics, and in particular in quantum computation, noises emerging from the interaction of a system with its surrounding environment is formulated in terms of the density matrix. The theory is well developed, but from the computational point of view resorting to the density matrix instead of the state vector makes the problem quadratically more difficult to solve.
We propose a scheme called Noisy Gates, that uses state vectors evolving according to a stochastic Schrödinger equation. This description is statistically equivalent to the density matrix formulation: by taking the average over different noise realizations, one recovers the evolution of the density matrix. At the same time, it presents the computational advantage of working with the state vector. Moreover, differently from the standard approach in which the gate and noise are decoupled, the solution of stochastic Schrödinger equations is a linear and stochastic matrix, mathematically equivalent to a quantum gate that mixes the effects of the noise with the unitary action of the gate. This provides a more accurate physical description and it gives our method its name, Noisy gates. By

finding the expressions for these noisy gates, one can perform classical simulations of noisy quantum algorithms on quantum computers, in order to analyze error propagation and devise strategies to mitigate them.