Opinions Libres
le blog d'Olivier Ezratty

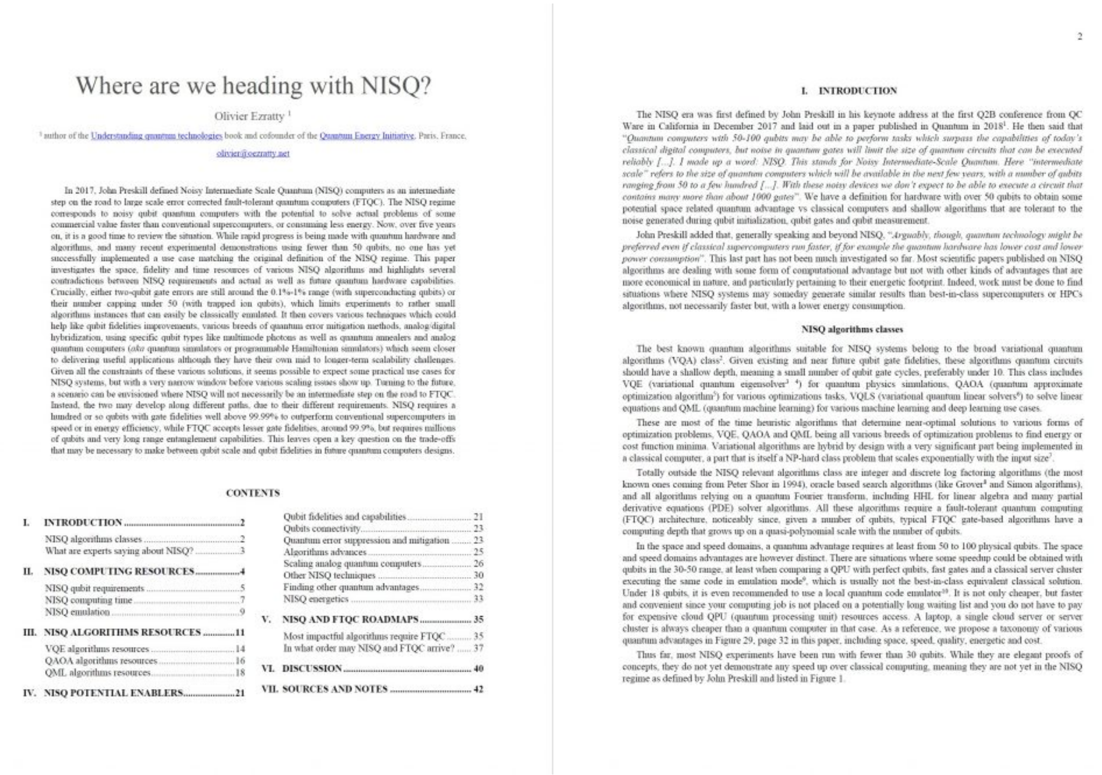
Where are we heading with NISQ?

I'm continuing a series of broad review papers on quantum computing after **Disentangling quantum emulation and quantum simulation** in January 2023, **Is there a Moore's law for quantum computing?** in March 2023 and **Perspective on superconducting qubit quantum computing** published in EPJA in April 2023.

This time, I evaluate the state of the art of noisy intermediate scale quantum computers (NISQ) and what can be done with it or not, and how it can improve in the near future. I lay out some inconvenient truths: NISQ is not at all ready for prime time quantum computing despite all the fuss about "quantum computing being business ready". Not only have we not yet reached any quantum computing advantage, but in many cases, even if it worked, the most common NISQ algorithms using a variational approach, have prohibitively long execution times particularly in the promising chemical simulations domain. Most documented gate-based NISQ algorithms use cases run with fewer than 20 qubits that can be emulated faster on a regular laptop costing less than $2K and even provide better results since they emulate perfect non noisy qubits. Also, there are significant inconsistencies between the criteria to reach some quantum advantage (>50 qubits, some computing depth) and the fidelities of the required physical qubits.

There is still hope to extract some value from NISQ quantum computers, mostly with analog quantum computers and with various other techniques related to the improvement of gate-based NISQ quantum computers, but probably within a rather narrow window, corresponding to the 100×100 (# qubits x computing depth) challenge proposed by IBM for its future Heron 133 qubits QPU.

You can download this paper on **arXiv**.



Where are we heading with NISQ?

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In 2017, John Preskill defined Noisy Intermediate Scale Quantum (NISQ) computers as an intermediate step on the road to large scale error corrected fault-tolerant quantum computers (FTQC). The NISQ regime corresponds to noisy qubit quantum computers with the potential to solve actual problems of some commercial value faster than conventional supercomputers, or consuming less energy. Now, over five years on, it is a good time to review the situation. While rapid progress is being made with quantum hardware and algorithms, and many recent experimental demonstrations using fewer than 50 qubits, no one has yet successfully implemented a use case matching the original definition of the NISQ regime. This paper investigates the space, fidelity and time resources of various NISQ algorithms and highlights several contradictions between NISQ requirements and actual as well as future quantum hardware capabilities. Crucially, either two-qubit gate errors are still around the 0.1%-1% range (with superconducting qubits) or their number capping under 50 (with trapped ion qubits), which limits experiments to rather small algorithms instances that can easily be classically emulated. It then covers various techniques which could help like qubit fidelities improvements, various breeds of quantum error mitigation methods, analog/digital hybridization, using specific qubit types like multimode photons as well as quantum annealers and analog quantum computers (*aka* quantum simulators or programmable Hamiltonian simulators) which seem closer to delivering useful applications although they have their own mid to longer-term scalability challenges. Given all the constraints of these various solutions, it seems possible to expect some practical use cases for NISQ systems, but with a very narrow window before various scaling issues show up. Turning to the future, a scenario can be envisioned where NISQ will not necessarily be an intermediate step on the road to FTQC. Instead, the two may develop along different paths, due to their different requirements. NISQ requires a hundred or so qubits with gate fidelities well above 99.99% to outperform conventional supercomputers in speed or in energy efficiency, while FTQC accepts lesser gate fidelities, around 99.9%, but requires millions of qubits and very long range entanglement capabilities. This leaves open a key question on the trade-offs that may be necessary to make between qubit scale and qubit fidelities in future quantum computers designs.

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I. INTRODUCTION

The NISQ era was first defined by John Preskill in his keynote address at the first Q2B conference from QC Ware in California in December 2017 and laid out in a paper published in Quantum in 2018[1]. He then said that "*Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably […]. I made up a word: NISQ. This stands for Noisy Intermediate-Scale Quantum. Here "intermediate scale" refers to the size of quantum computers which will be available in the next few years, with a number of qubits ranging from 50 to a few hundred […]. With these noisy devices we don't expect to be able to execute a circuit that contains many more than about 1000 gates*". We have a definition for hardware with over 50 qubits to obtain some potential space related quantum advantage vs classical computers and shallow algorithms that are tolerant to the noise generated during qubit initialization, qubit gates and qubit measurement.

John Preskill added that, generally speaking and beyond NISQ, "*Arguably, though, quantum technology might be preferred even if classical supercomputers run faster, if for example the quantum hardware has lower cost and lower power consumption*". This last part has not been much investigated so far. Most scientific papers published on NISQ algorithms are dealing with some form of computational advantage but not with other kinds of advantages that are more economical in nature, and particularly pertaining to their energetic footprint. Indeed, work must be done to find situations where NISQ systems may someday generate similar results than best-in-class supercomputers or HPCs algorithms, not necessarily faster but, with a lower energy consumption.

NISQ algorithms classes

The best known quantum algorithms suitable for NISQ systems belong to the broad variational quantum algorithms (VQA) class[2]. Given existing and near future qubit gate fidelities, these algorithms quantum circuits should have a shallow depth, meaning a small number of qubit gate cycles, preferably under 10. This class includes VQE (variational quantum eigensolver[3 4]) for quantum physics simulations, QAOA (quantum approximate optimization algorithm[5]) for various optimizations tasks, VQLS (variational quantum linear solvers[6]) to solve linear equations and QML (quantum machine learning) for various machine learning and deep learning use cases.

These are most of the time heuristic algorithms that determine near-optimal solutions to various forms of optimization problems, VQE, QAOA and QML being all various breeds of optimization problems to find energy or cost function minima. Variational algorithms are hybrid by design with a very significant part being implemented in a classical computer, a part that is itself a NP-hard class problem that scales exponentially with the input size[7].

Totally outside the NISQ relevant algorithms class are integer and discrete log factoring algorithms (the most known ones coming from Peter Shor in 1994), oracle based search algorithms (like Grover[8] and Simon algorithms), and all algorithms relying on a quantum Fourier transform, including HHL for linear algebra and many partial derivative equations (PDE) solver algorithms. All these algorithms require a fault-tolerant quantum computing (FTQC) architecture, noticeably since, given a number of qubits, typical FTQC gate-based algorithms have a computing depth that grows up on a quasi-polynomial scale with the number of qubits.

In the space and speed domains, a quantum advantage requires at least from 50 to 100 physical qubits. The space and speed domains advantages are however distinct. There are situations where some speedup could be obtained with qubits in the 30-50 range, at least when comparing a QPU with perfect qubits, fast gates and a classical server cluster executing the same code in emulation mode[9], which is usually not the best-in-class equivalent classical solution. Under 18 qubits, it is even recommended to use a local quantum code emulator[10]. It is not only cheaper, but faster and convenient since your computing job is not placed on a potentially long waiting list and you do not have to pay for expensive cloud QPU (quantum processing unit) resources access. A laptop, a single cloud server or server cluster is always cheaper than a quantum computer in that case. As a reference, we propose a taxonomy of various quantum advantages in Figure 29, page 32 in this paper, including space, speed, quality, energetic and cost.

Thus far, most NISQ experiments have been run with fewer than 30 qubits. While they are elegant proofs of concepts, they do not yet demonstrate any speed up over classical computing, meaning they are not yet in the NISQ regime as defined by John Preskill and listed in Figure 1.

If you are interested by the advent of FTQC (scalable fault-tolerant quantum computing), my recent **arXiv** on Moore's law in quantum computing is a good starter.

Thanks a lot to Alain Chancé (Molket), Vincent Elfving (Pasqal), Marco Fellous-Asiani (Centre of New Technologies University of Warsaw), Loïc Henriet (Pasqal), Michel Kurek (Multiverse), Jean-Baptiste Latre (Qualitative Computing), Joseph Mikael (EDF), Stéphane Requena (HQI/GENCI), Jean Senellart (Quandela), Simone Severini (AWS), Robert Whitney (CNRS LPMMC, QEI), Xavier Waintal (CEA IRIG) and Raja Yehia (ICFO) for their feedback on the paper, which doesn't mean an endorsement of all its content.

I also recognize useful discussions with and insights from Alexia Auffèves (CNRS MajuLab, CQT, QEI), Cyrille Allouche (Atos/Eviden), Thomas Ayral (Atos/Eviden), Jerry Chow (IBM), Jay Gambetta (IBM), John Preskill (Caltech), and Pierre Perrot (Eureptech).

I wrote this paper from February to May 2023 and I am ready to correct errors and complement it for a subsequent release!

Cet article a été publié le 17 mai 2023 et édité en PDF le 16 mars 2024.