Michael de Oliveira

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Thesis titled "On Quantum Bayesian Decision Making"

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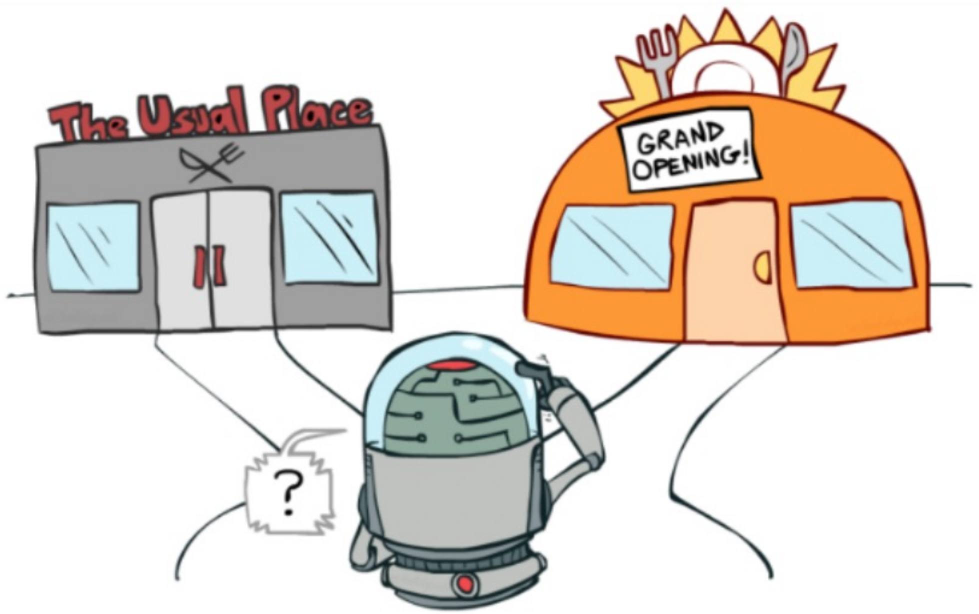
Upcoming- Research Scientist Foxconn

Research on quantum complexity theory and quantum algorithms

My Master’s thesis

Automated decision making processs

We are presented every day with multiple decision to make.



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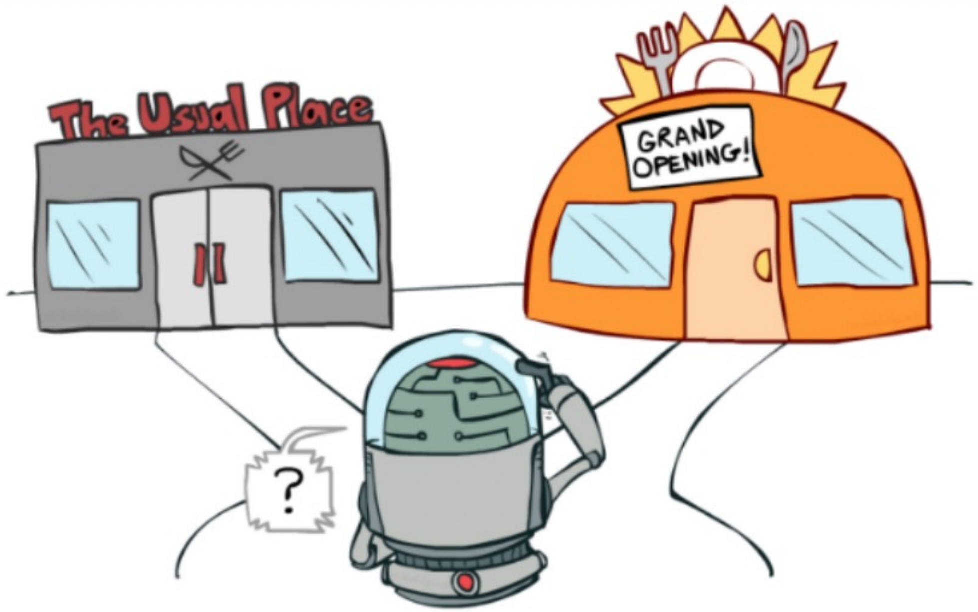

However, we would like to delegate most of them to a kind of personal assistant who can make near-optimal decisions for us.

Automated decision making processs

First, we need a mathematical model that can describe probabilistic systems to handle uncertainty.

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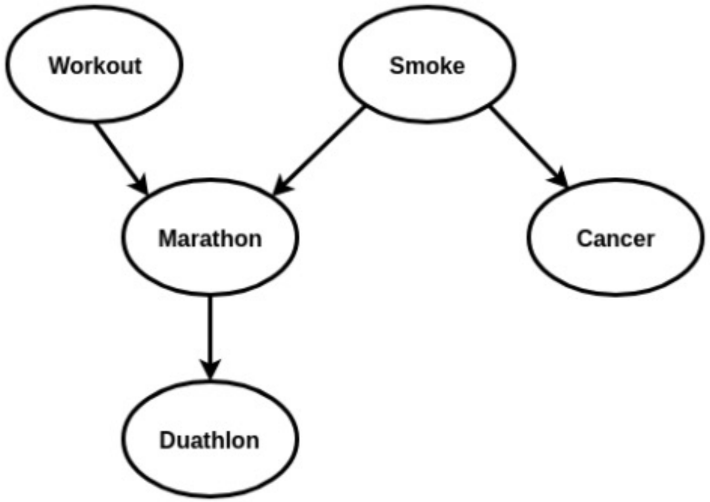
Bayesian networks



Workout	P(Workout)
True	0.7
False	0.3

Smoke	P(Smoke)
True	0.6
False	0.4

Smoke	Workout	Marathon	P(Marathon | Workout,Smoke)
True	True	True	0.2
True	True	False	0.8
True	False	True	0.05
True	False	False	0.95
False	True	True	0.4
False	True	False	0.6
False	False	True	0.1
False	False	False	0.9

Smoke	Lung cancer	P(Lung cancer | Somke)
True	True	0.02
True	False	0.98
False	True	0.005
False	False	0.995

Marathon	Duathlon	P(Duathlon | Marathon)
True	True	0.7
True	False	0.3
False	True	0
False	False	1

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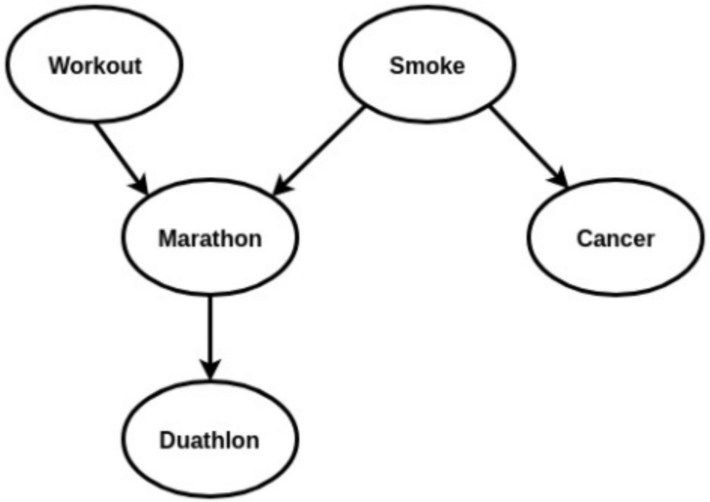
Bayesian networks



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True	True	0.7
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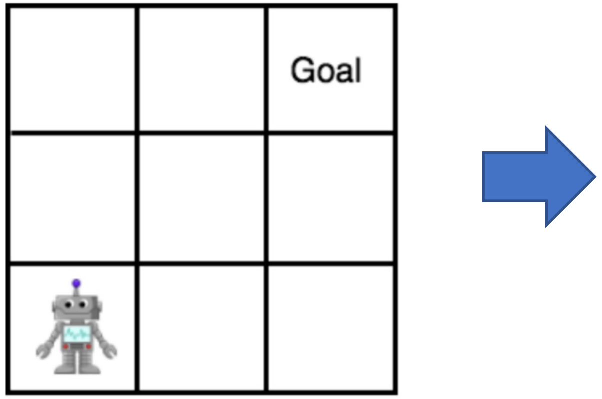
False	True	0
False	False	1

$$P(x_1, \dots, x_n) = \prod_{i=1}^{n} P(x_i | Parents(X_i))$$

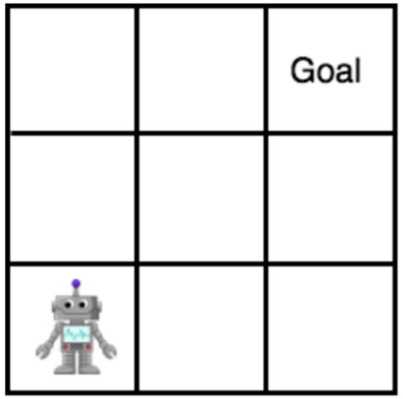
Automated decision making processs

Problem

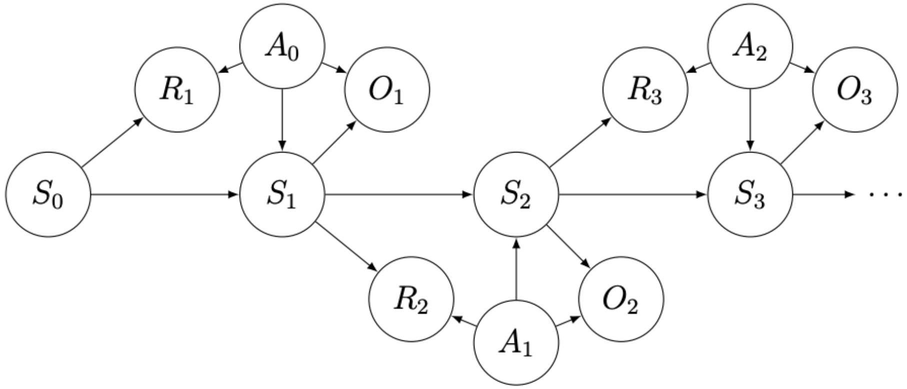


Automated decision making processs

<u>Problem</u>

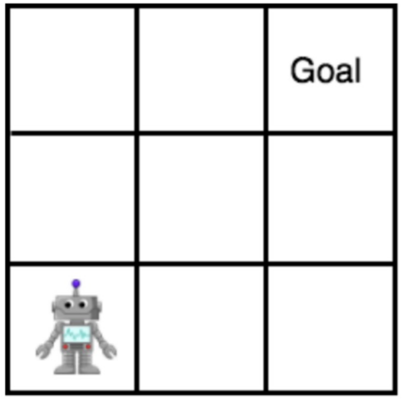


<u>Model/abstraction</u>



Automated decision making processs

Problem



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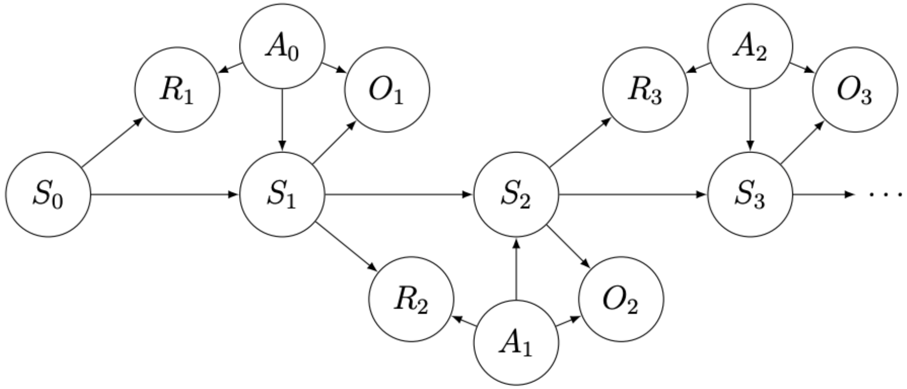


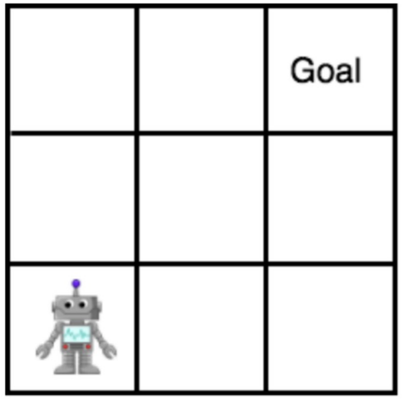
Decision making process

Cumpute $A_1, A_2, \ldots, A_n$

s.t. $R_T = \sum_{i=1}^{n} R_i$ is maximal

Automated decision making processs

Problem



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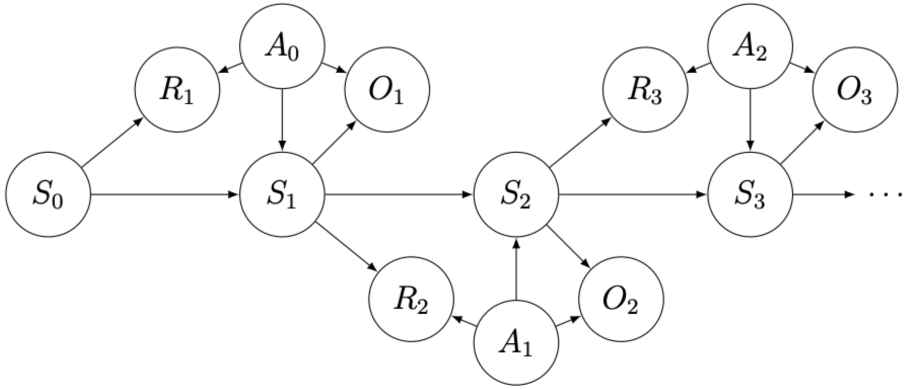

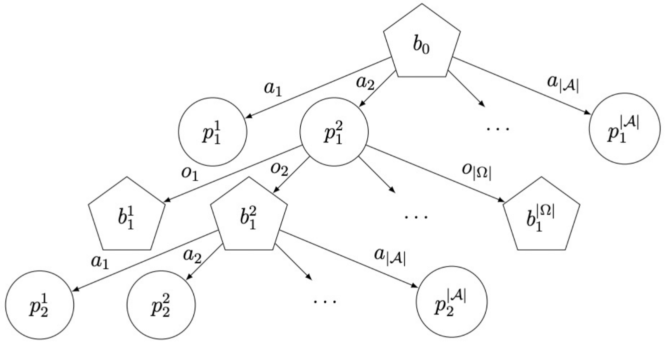

Decision making process

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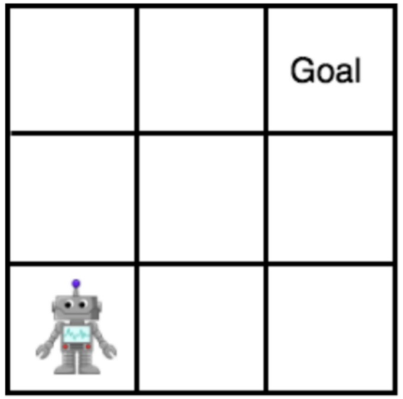
It exponentially harder to interpolate over each additional time step

Automated decision making processs

Problem



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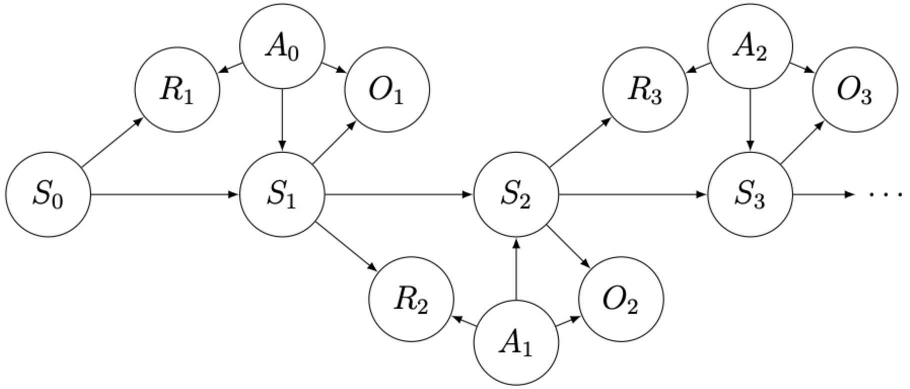

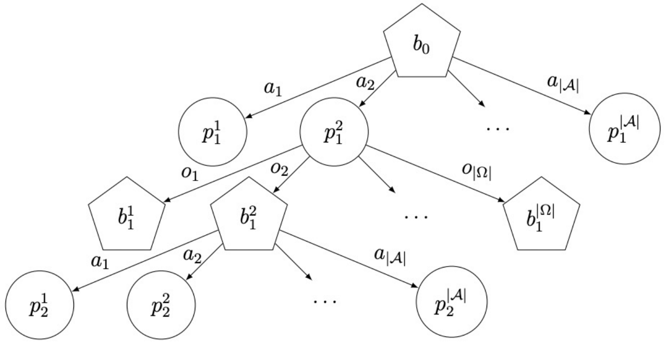

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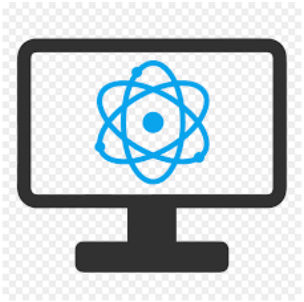
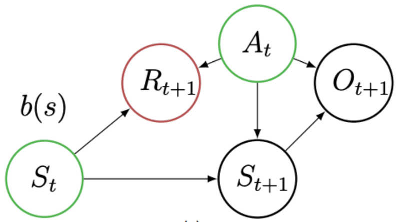


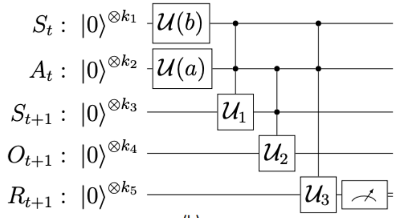
Cumpute $A_1, A_2, \dots, A_n$

Naïve quantum Bayesian decision making process

Quantum bayesian network states



(a)



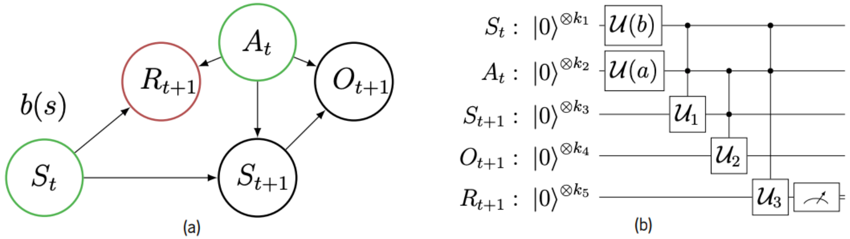
(b)

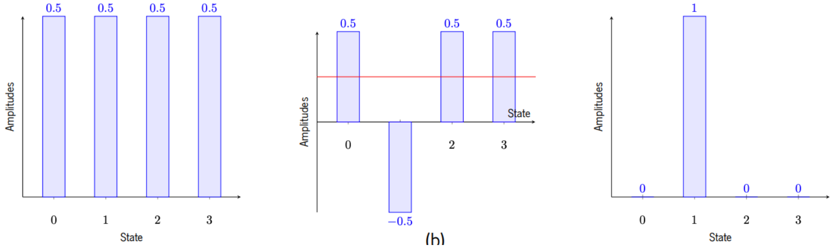
Naïve quantum Bayesian decision making process

Quantum bayesian network states

+

Amplitude amplification algorithm





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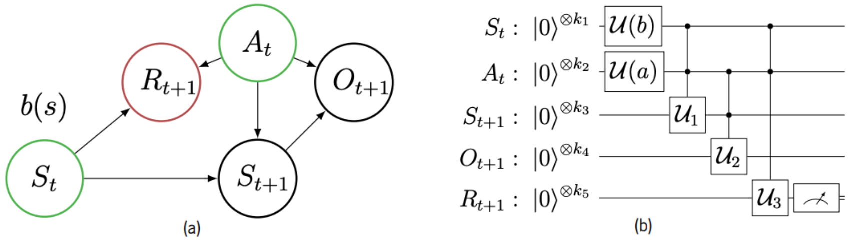

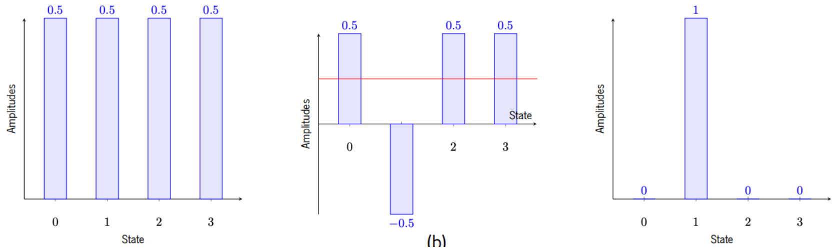

	Classical	Quantum
Complexity	$\mathcal{O}\left(NMP(e)^{-1}\right)$	$\mathcal{O}\left(N2^{M}P(e)^{-\frac{1}{2}}\right)$

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Quantum bayesian network states

+

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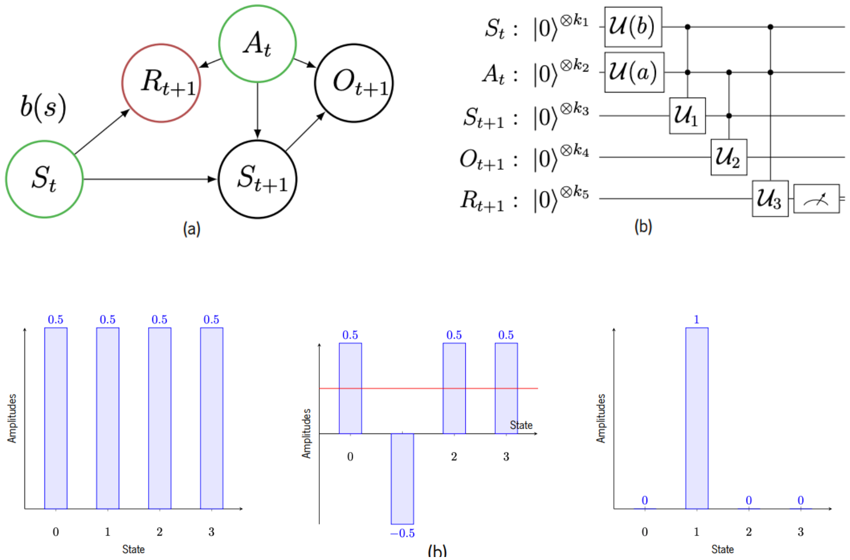

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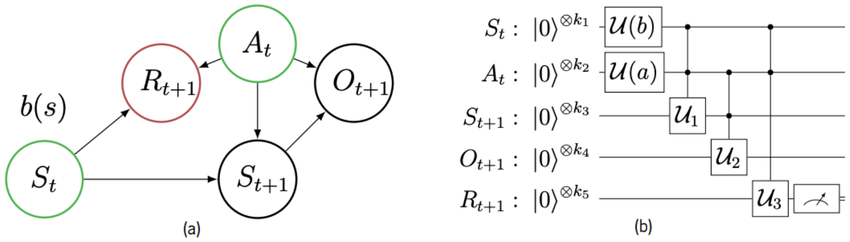
$$EU(a|e) = \sum_{r} \underbrace{P(Result = r|a, e)}_{Quantum} * \underbrace{U(r)}_{Classical}$$

$$action = argmax_{a} EU(a|e)$$

Naïve quantum Bayesian decision making process

Quantum bayesian network states



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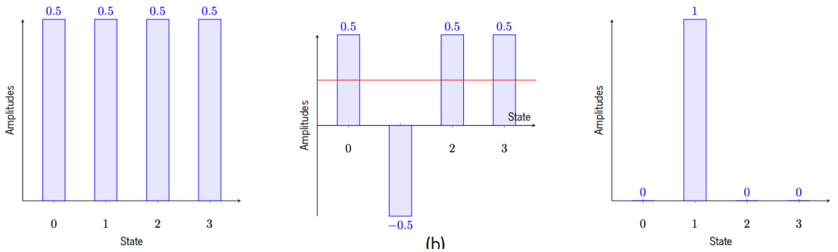
Amplitude amplification algorithm



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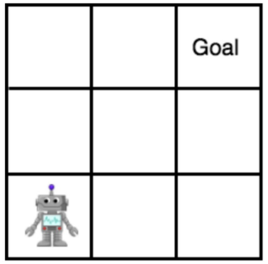
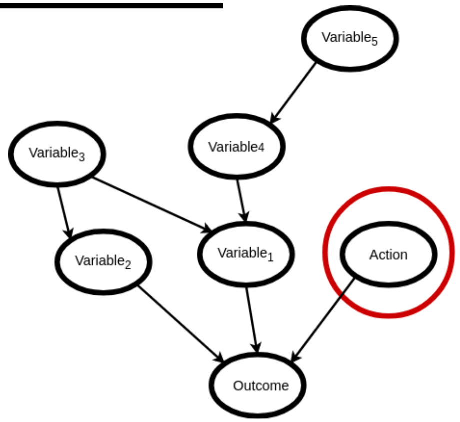
We obtain subquadratic quantum advantages for sparse Bayesian networks.



A new Quantum Bayesian Decision-Making

Condition



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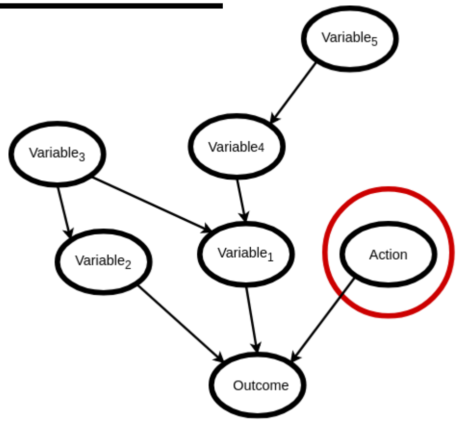
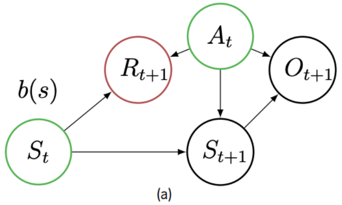
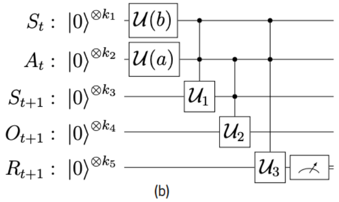


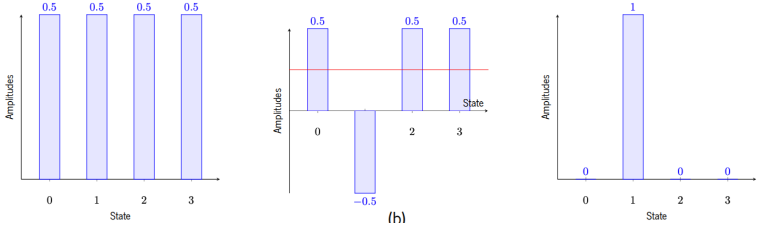
Solution

- We encode the BN but do not select an action





- We amplify the observation v. and the outcome v. based on their utility.



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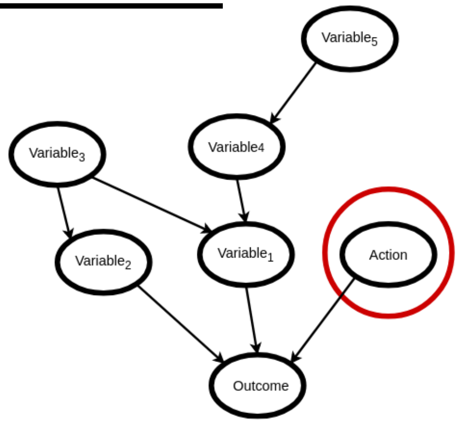

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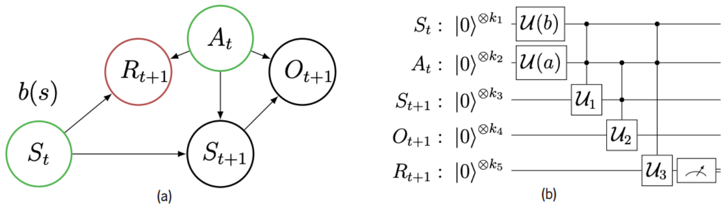

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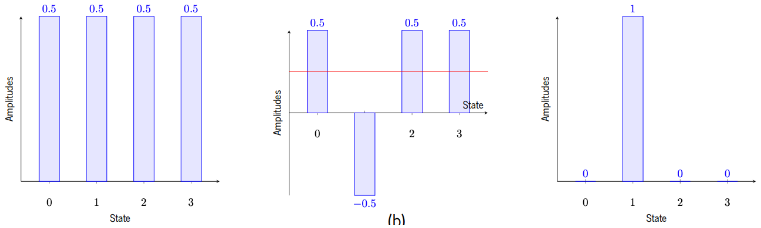
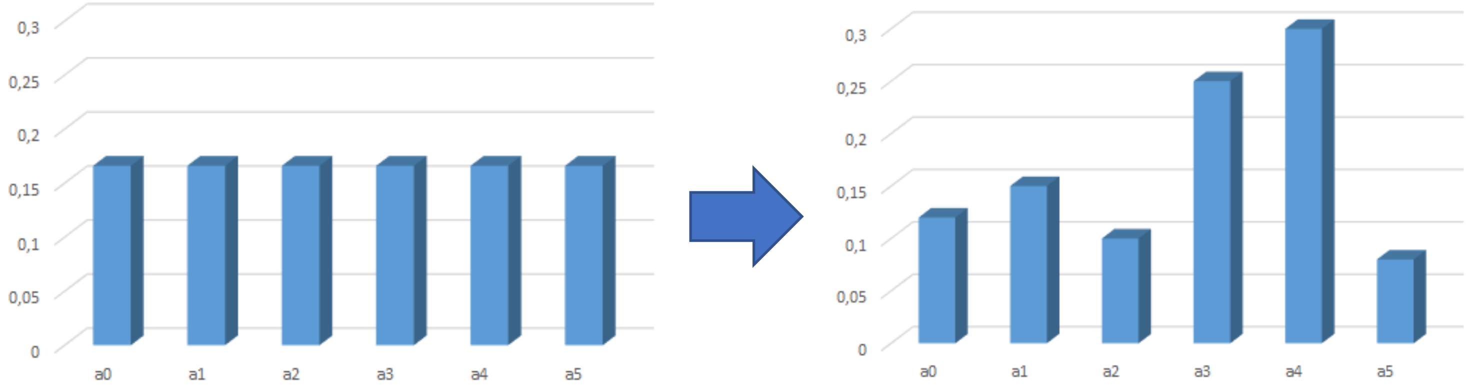


Consequence



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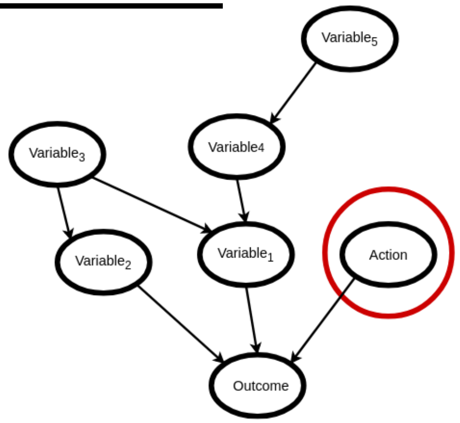

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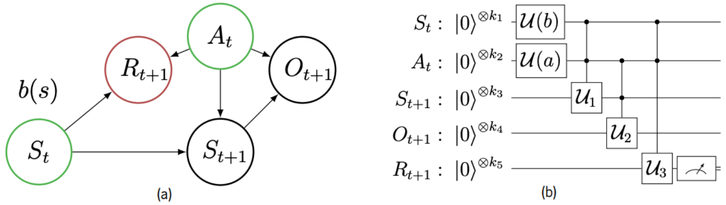

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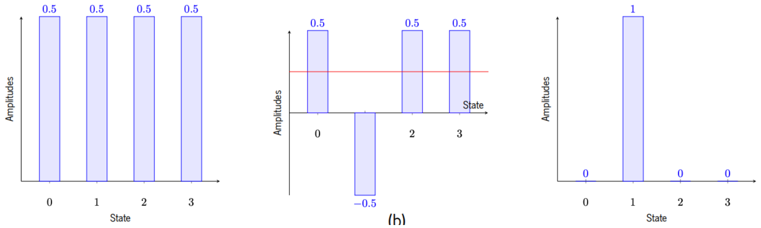

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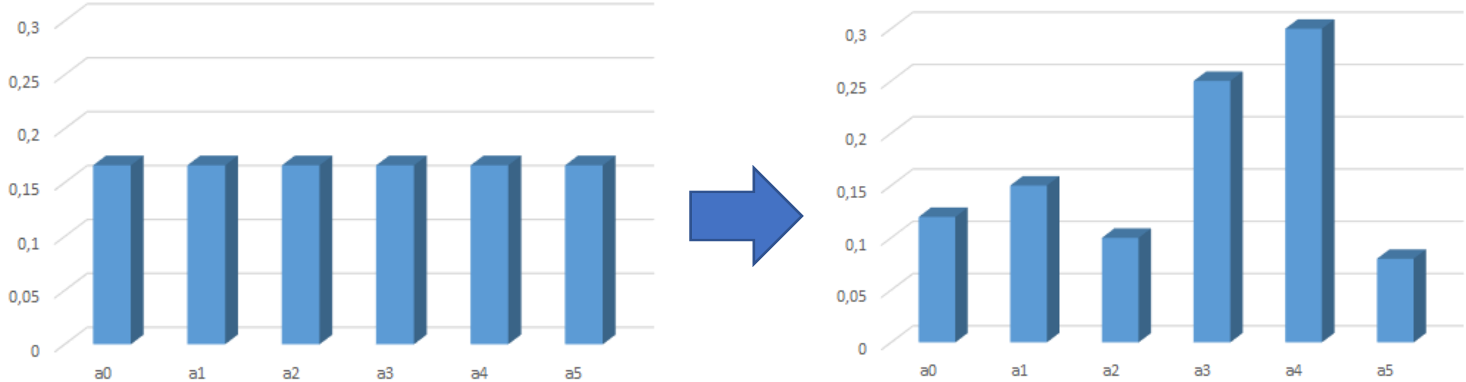

Result

For sparse Bayesian networks, we obtain a subquadratic quantum advantage but a strictly larger advantage than naïve amplitude amplification.

$$\frac{C}{Q_{naive}} = n^{c_1}, \qquad \frac{C}{Q_{new}} = n^{c_2}$$

$$c_1 < c_2$$

On Quantum Bayesian Decision-Making

This work and its results gave origin to,

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Presentation at an international workshop (Santiago Chile)

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Foundations of Science (2023) 28:21–41
https://doi.org/10.1007/s10699-021-09781-6

Quantum Bayesian Decision-Making

Michael de Oliveira[1] · Luis Soares Barbosa[1]

Published online: 20 March 2021

Abstract
As a compact representation of joint probability distributions over a dependence graph of random variables, and a tool for modelling and reasoning in the presence of uncertainty, Bayesian networks are of great importance for artificial intelligence to combine domain knowledge, capture causal relationships, or learn from incomplete datasets. Known as a NP-hard problem in a classical setting, Bayesian inference pops up as a class of algorithms worth to explore in a quantum framework. This paper explores such a research direction and improves on previous proposals by a judicious use of the utility function in an entangled configuration. It proposes a completely quantum mechanical decision-making process with a proven computational advantage. A prototype implementation in Qiskit (a Python-based program development kit for the IBM Q machine) is discussed as a proof-of-concept.

Keywords Bayesian inference · Quantum algorithms · Quantum decision making

1 Motivation

Bayesian reasoning is widely used in machine learning and data science, as a powerful framework for probabilistic analysis, applications ranging from learning processes (Neal 1996) to pragmatic representations (Li et al. 2018). Broadly speaking, machine learning algorithms are able to learn from data, with the purpose of performing some tasks, without requiring explicit programming; in a sense outcomes are directly built by the sampled data. However, the current rate of data creation is almost exponential Al-Jarrah et al. (2015) (going, for example, from 3.5 million text messages per minute in 2016, to

This work is financed by the ERDF–European Regional Development Fund through the Operational Programme for Competitiveness and Internationalisation–COMPETE 2020 Programme and by National Funds through the Portuguese funding agency, FCT, within project POCI-01-0145-FEDER-030947. The first author was further supported by project NORTE-01-0145-FEDER-000037, funded by Norte Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement.

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Springer

A paper in a scientific journal

On Quantum Bayesian Decision-Making

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Check for updates

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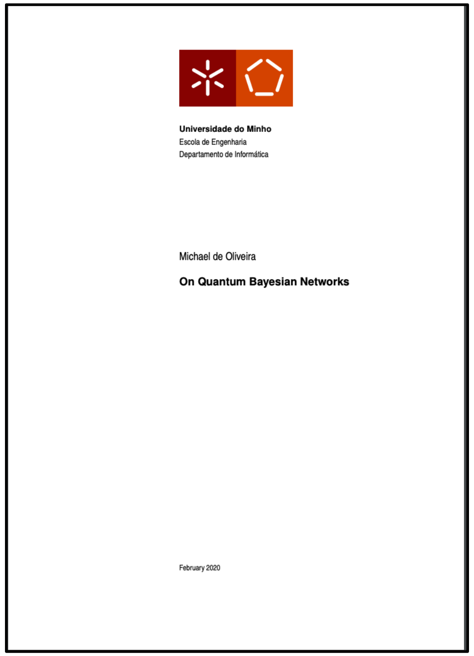

Universidade do Minho
Escola de Engenharia
Departamento de Informática

Michael de Oliveira

On Quantum Bayesian Networks

February 2020

Content of my Gulbenkian research project and master's thesis

My Phd thesis and the quest for realizable quantum computational advantages

Quantum advantage computational advantage

Main interest in quantum comes from the fact that these devices have **computation complexity theoretic implications**.

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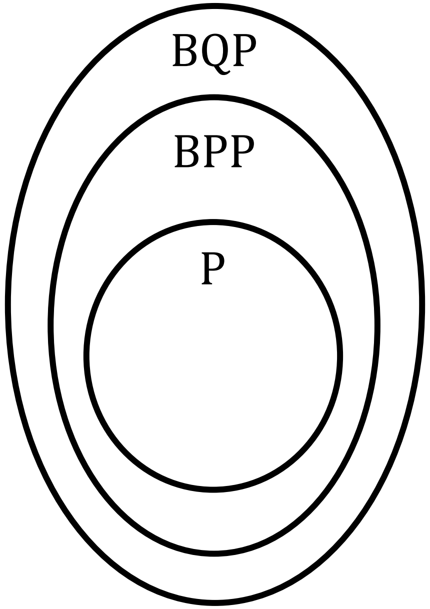
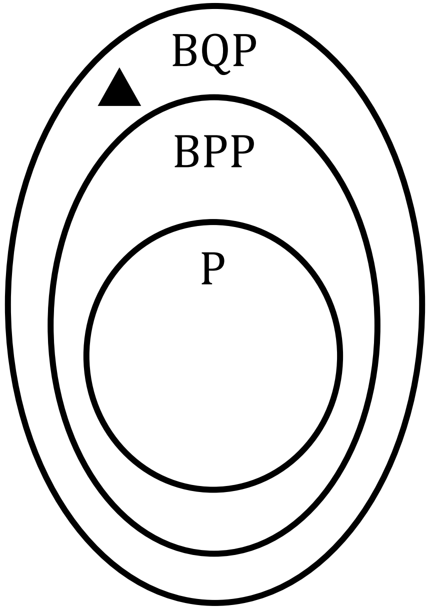


Quantum advantage computational advantage

Main interest in quantum comes from the fact that these devices have **computation complexity theoretic implications**.

- ▲ Shor's algorithm prime factorization is conjectured to separate BPP from BQP.



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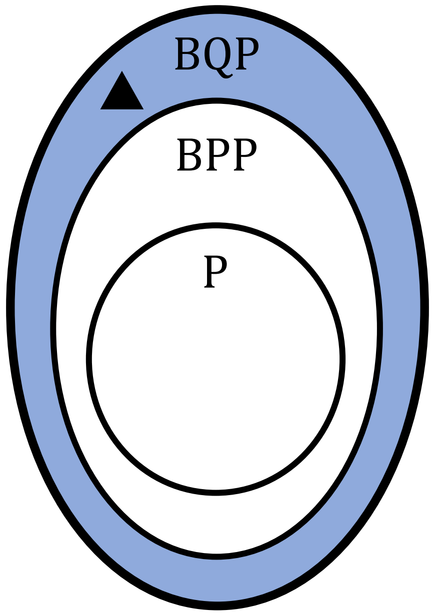

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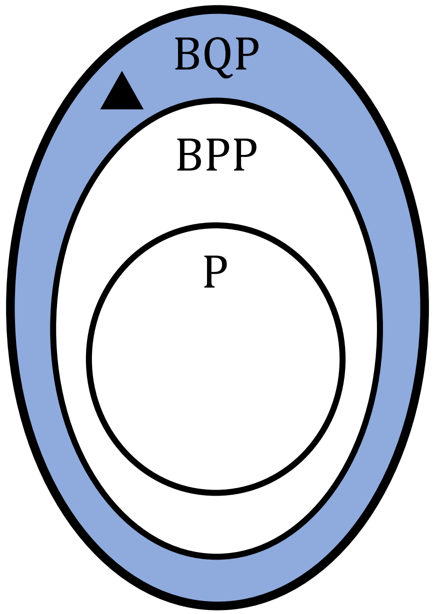
- Nevertheless, these quantum algorithms require **large-scale fault-tolerant quantum devices** (1700 qubits, 10^{36} Toffoli gates).



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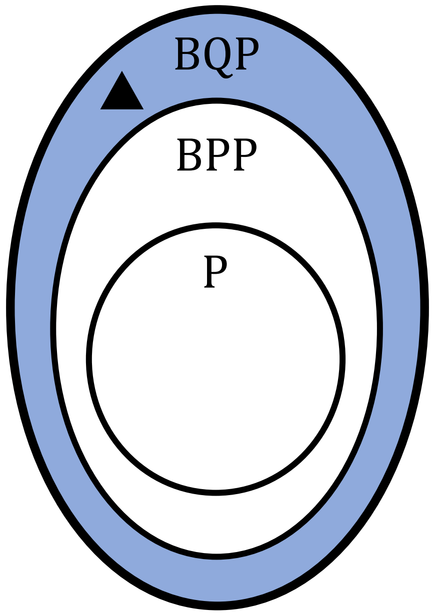
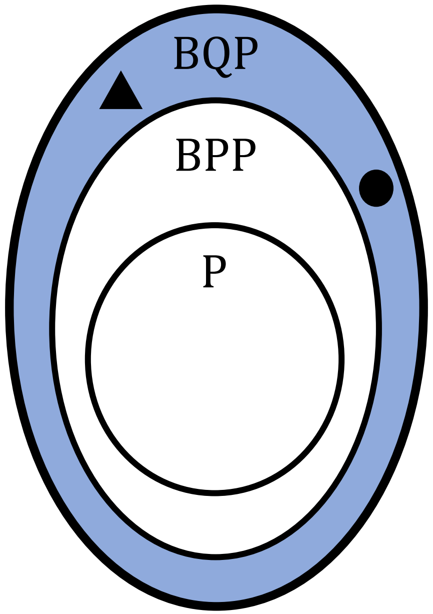
▲ Shor's algorithm prime factorization is conjectured to separate BPP from BQP.

- In simple terms it means that there exist quantum algorithms with **exponential advantages** over any possible classical algorithm.
- Nevertheless, these quantum algorithms require **large-scale fault-tolerant quantum devices** (1700 qubits, 10^{36} Toffoli gates).



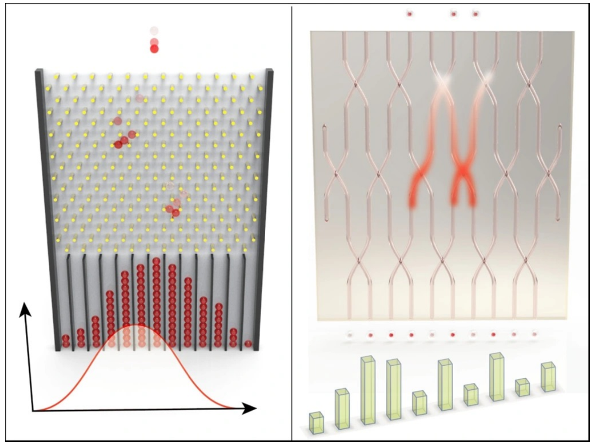
These algorithms (including Grover type search) are **not within reach in the next years** …

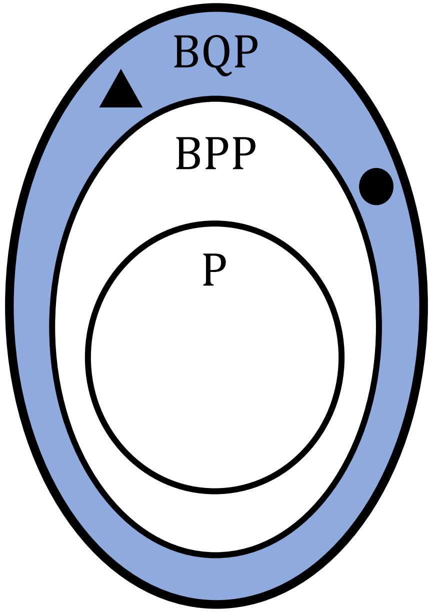
Quantum advantage within NISQ or LISQ regime



Quantum advantage within NISQ or LISQ regime

● Boson Sampling





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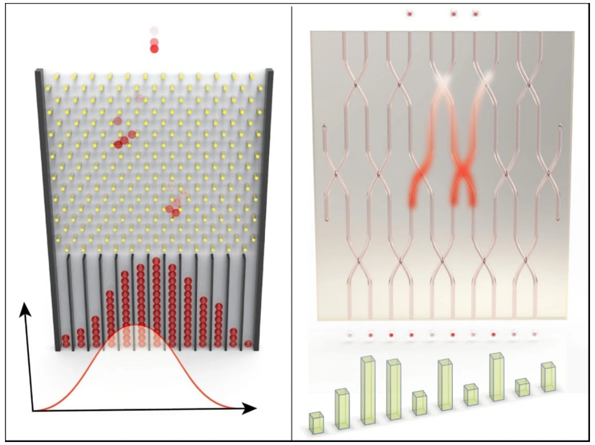
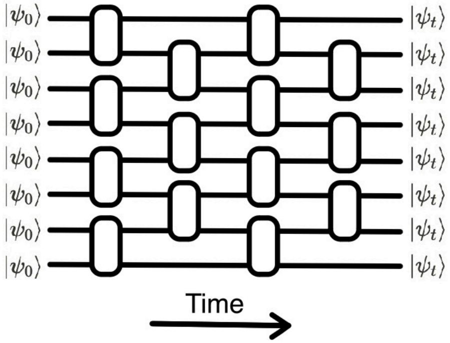
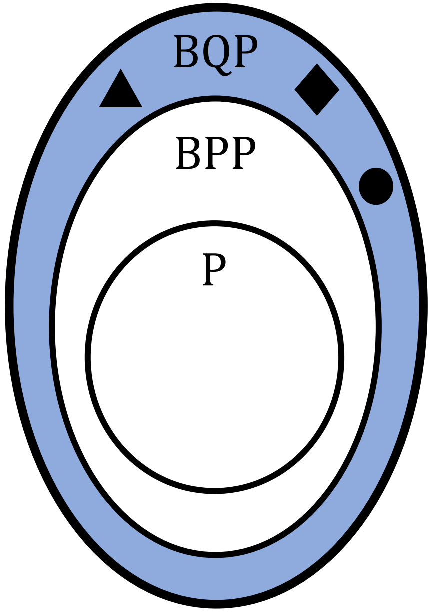


◆ Random circuit sampling





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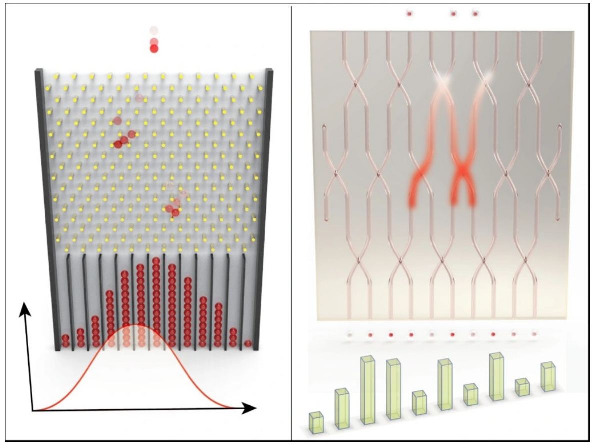
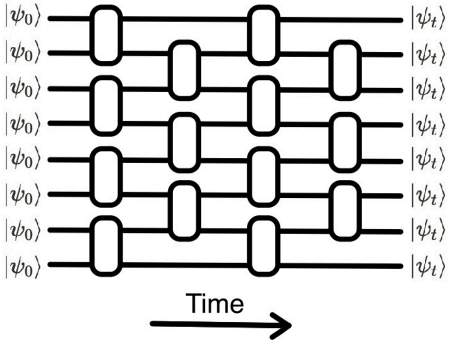
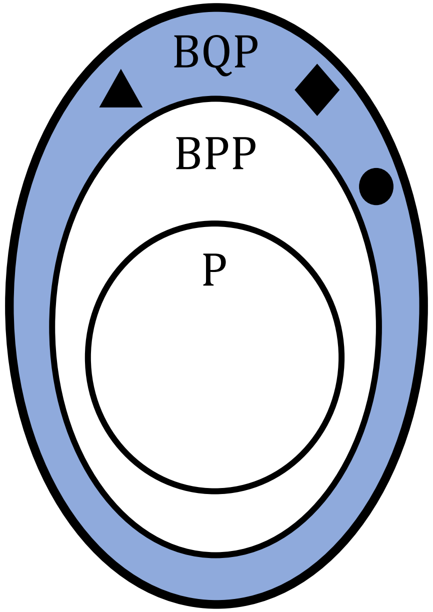




10^{25} *years*



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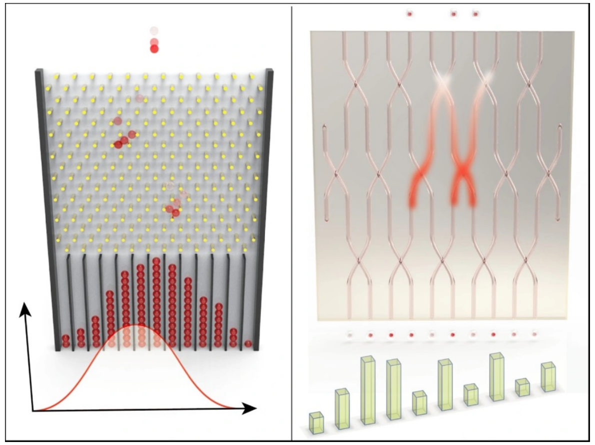

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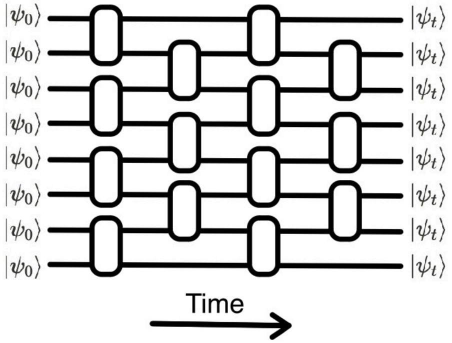

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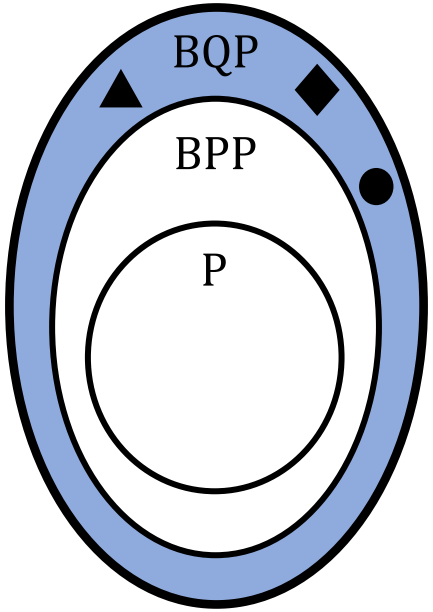

+ Shallow depth small quantum devices.

Quantum advantage within NISQ or LISQ regime

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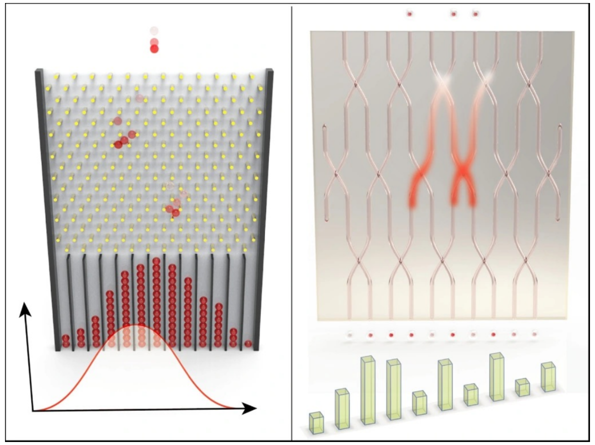

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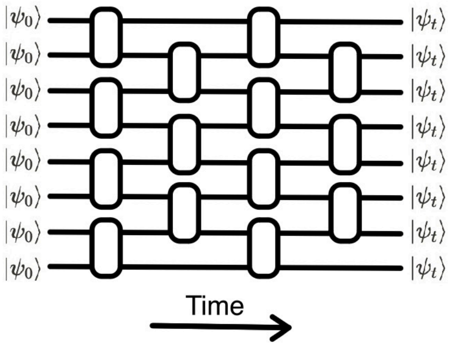

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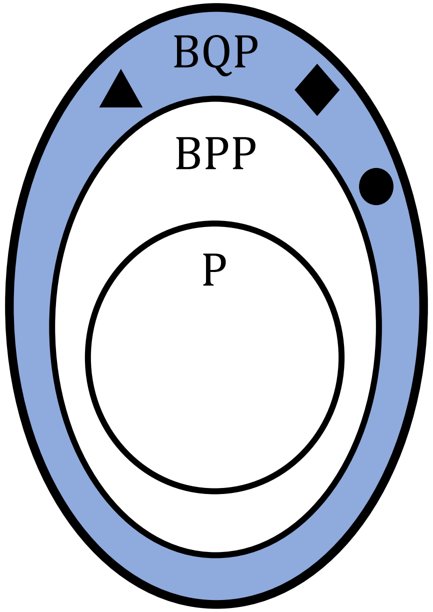

+ Shallow depth small quantum devices.

- Assuming the Polynomial Hierarchy does not collapse to the second level.

Quantum advantage within NISQ or LISQ regime

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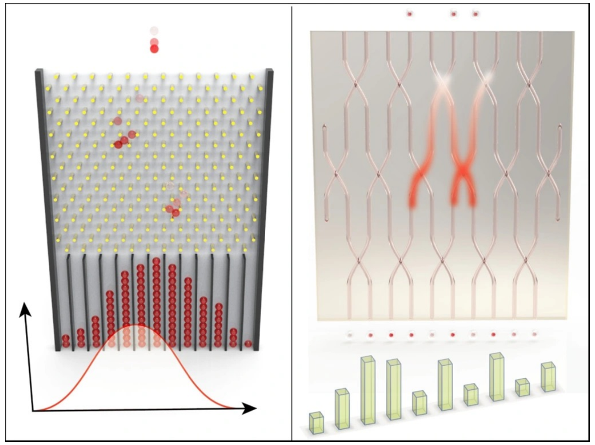

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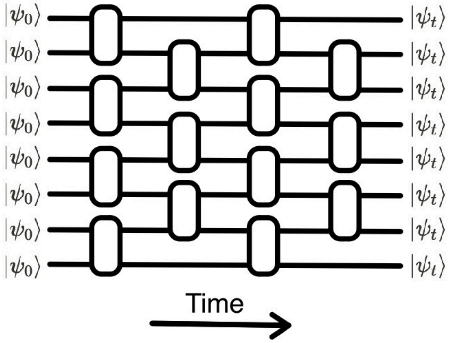

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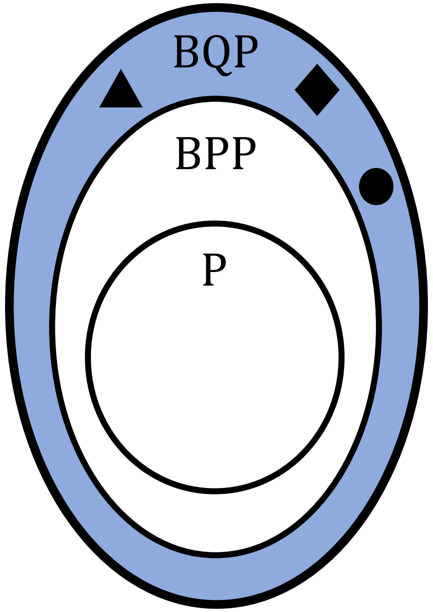

+ Shallow depth small quantum devices.

- Assuming the Polynomial Hierarchy does not collapse to the second level.

- It is hard to verify their correctness in the presence of noise.

Can we prove quantum advantage for any computational problem without relying on computational assumptions?

Unconditional quantum advantage within NISQ or LISQ regime

Can we prove quantum advantage for any computational problem without relying on assumptions?

Yes, if we fix time/depth to be constant!!!

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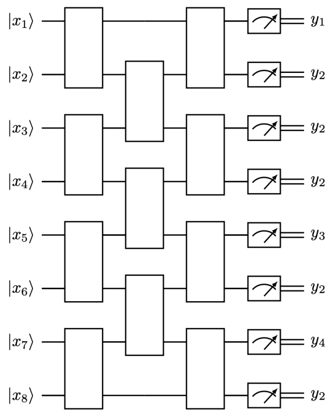
QNC^0



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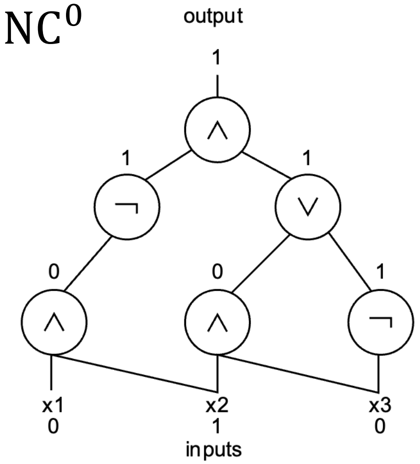

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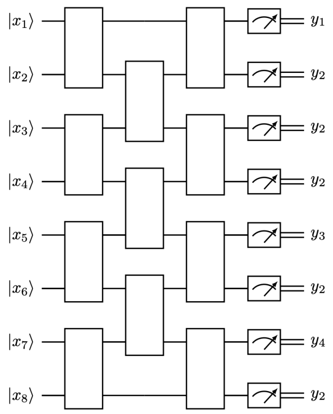

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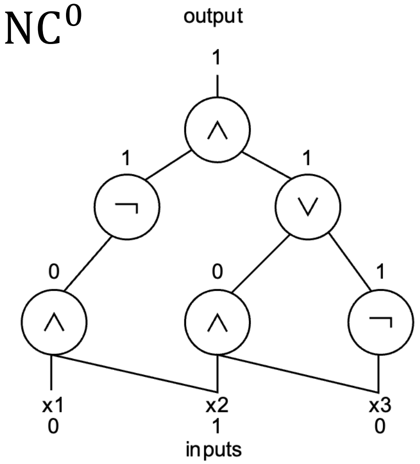

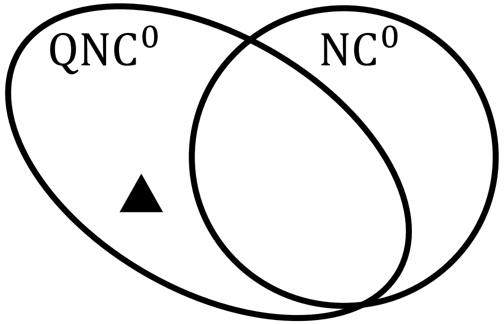

$QNC^0 \not\subseteq NC^0$

Hidden Linear shift problem ▲

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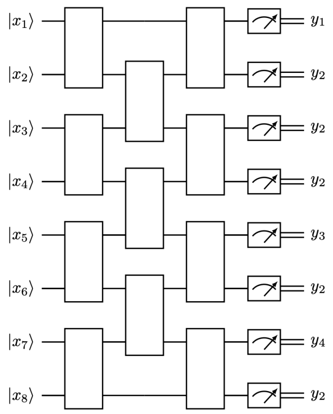

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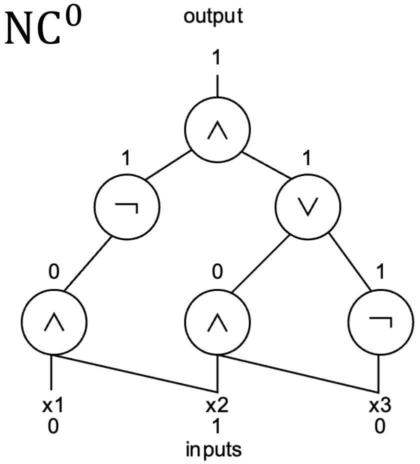

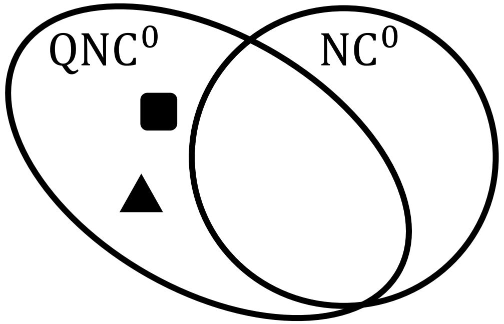

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1D Magic square problem ■

⋮

+ Error-robust.

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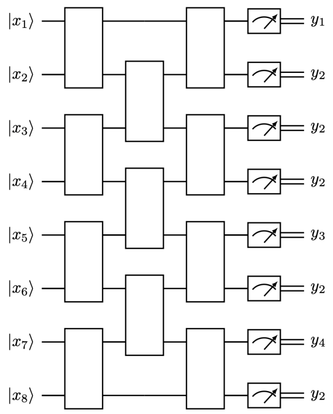

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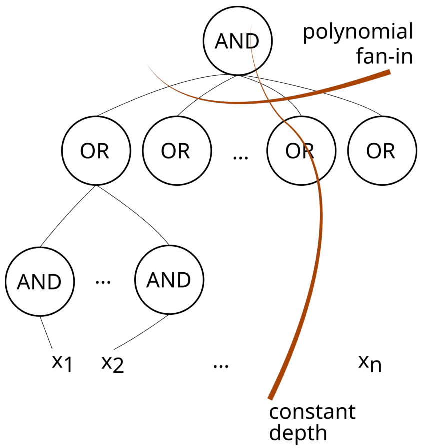
AC^0



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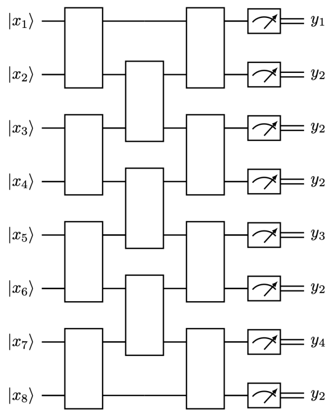
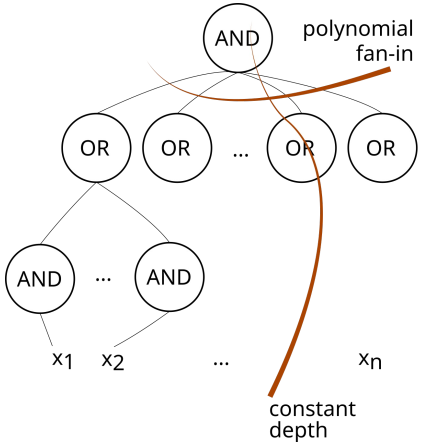
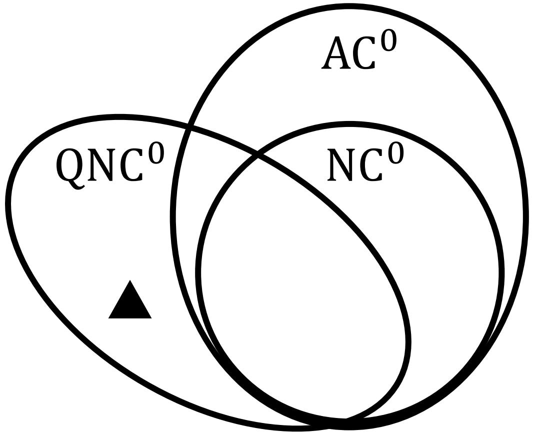
QNC^0 > AC^0







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Parity halving problem ▲

\+ Average-case hardness.

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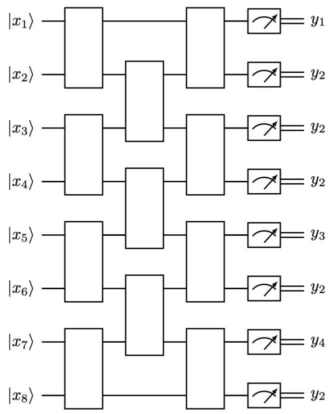

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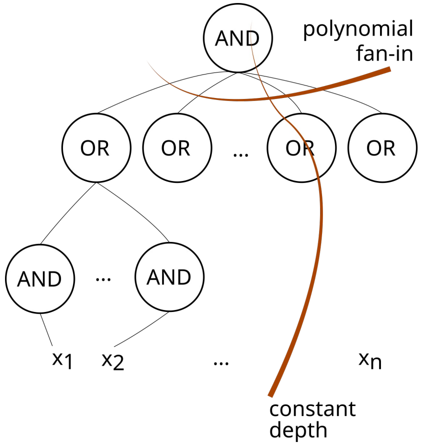

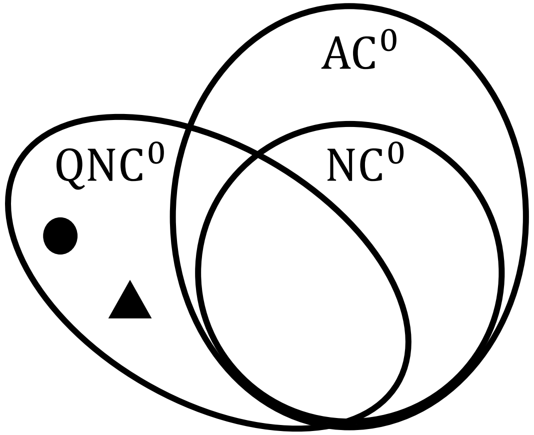

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Single-qubit teleportation ●

+ Noise resilient.

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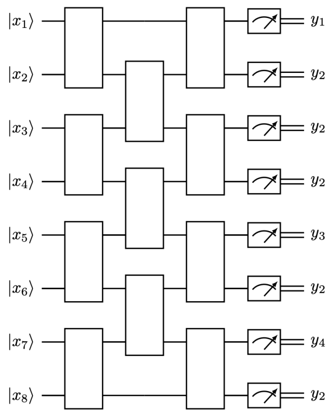

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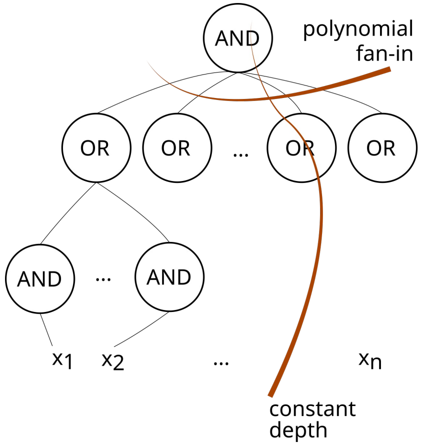

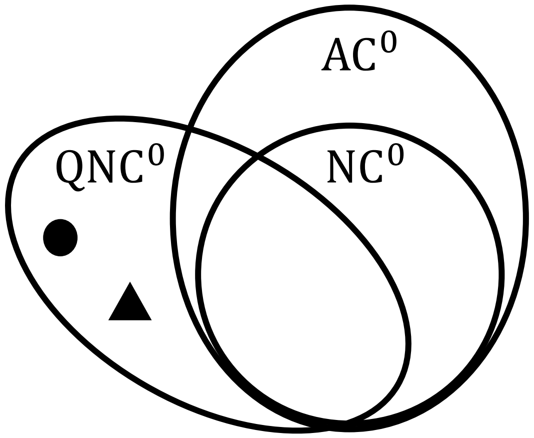

▲ $\mathrm{QNC}^0 \not\subseteq \mathrm{AC}^0$

Parity halving problem ▲

+ Average-case hardness.
- AC^0 circuit class is of rather small practical use.

Single-qubit teleportation ●

+ Noise resilient.

How powerfull are constant-depth quantum circuits?

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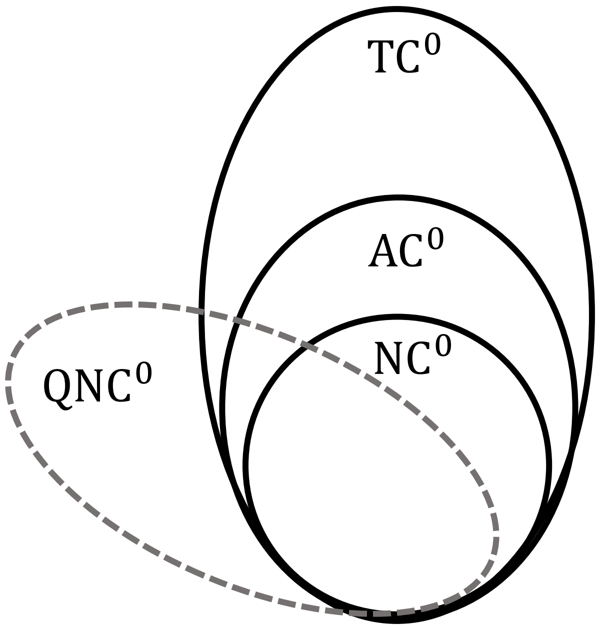

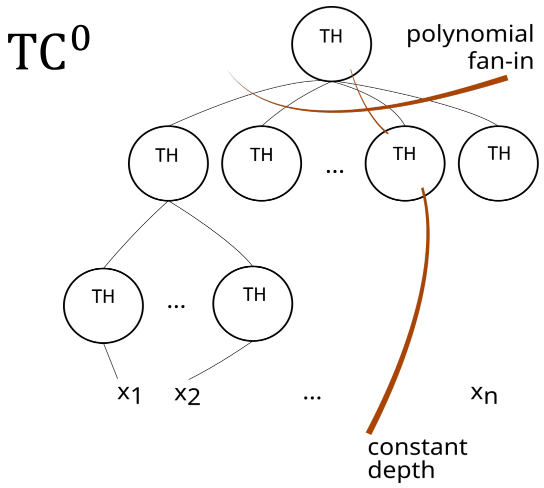

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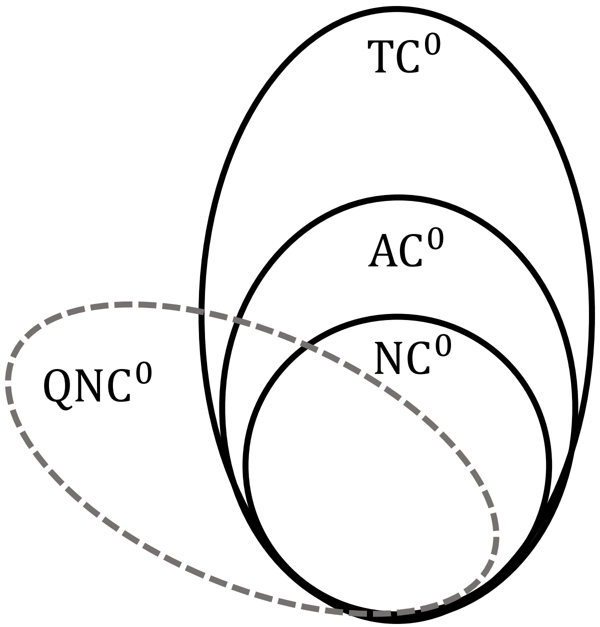

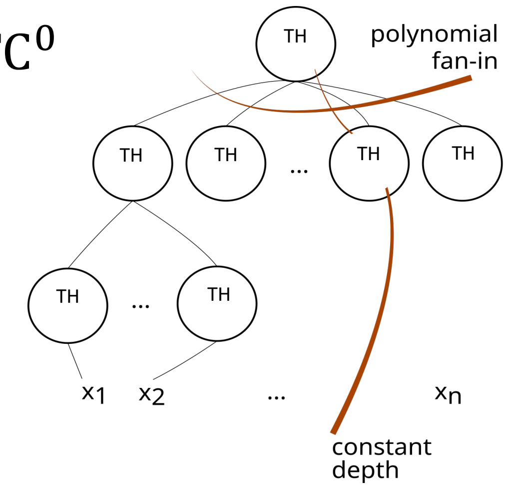

- TC^{0}circuits are able a large set of algebraic problems

Integer Multiplication, Division, Sorting, ...

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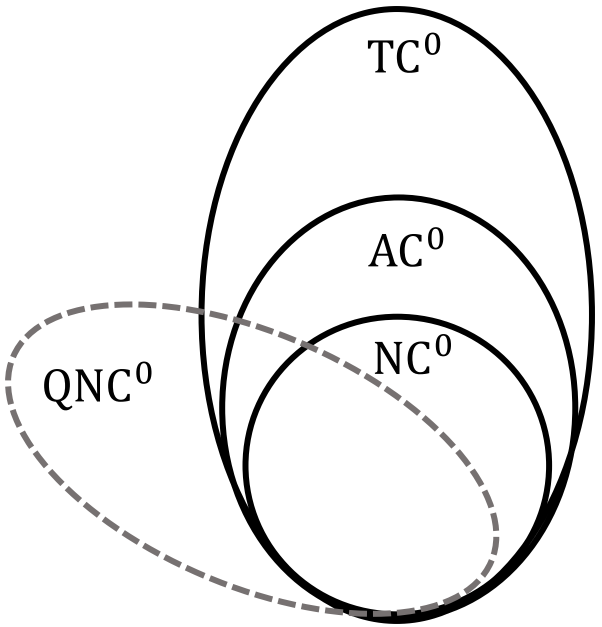

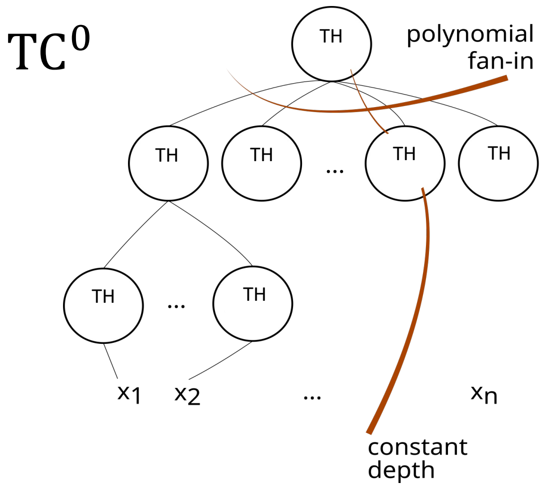

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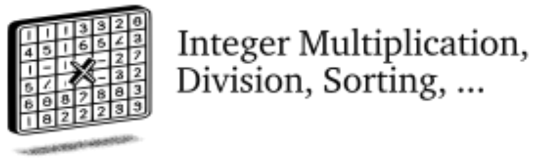
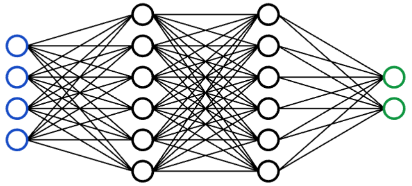


- TC^0 circuits serve as the circuit class that models Neural Networks (including LLMs)



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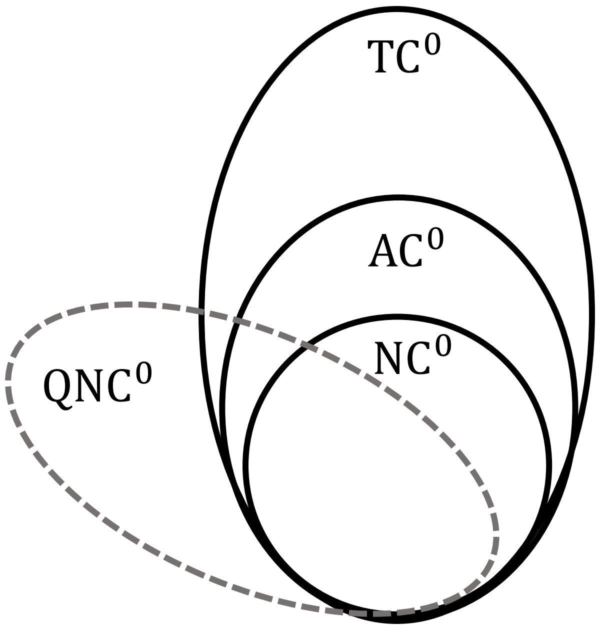

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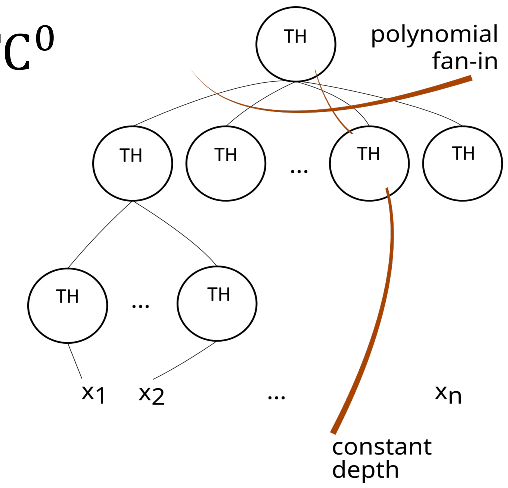

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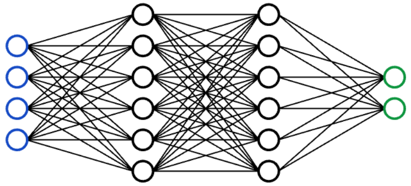

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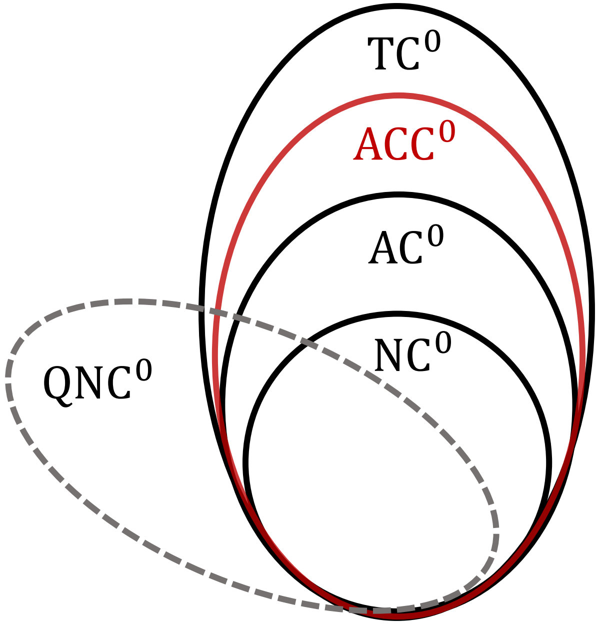
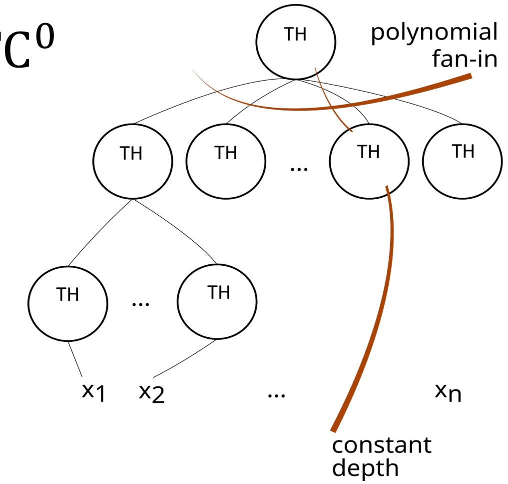


$E^{NP} \not\subseteq ACC^0$ [Williams16]

TC^0



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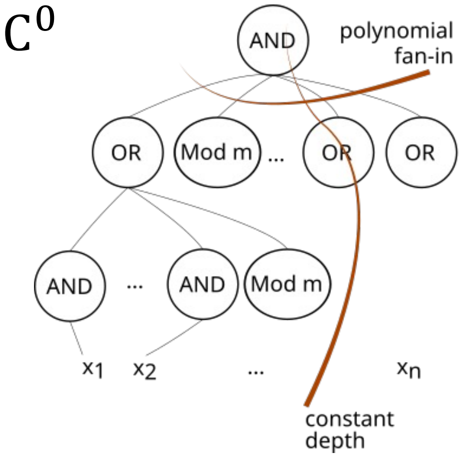

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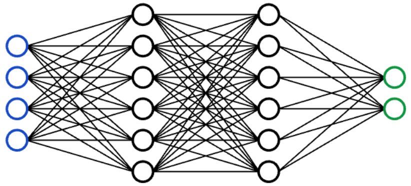

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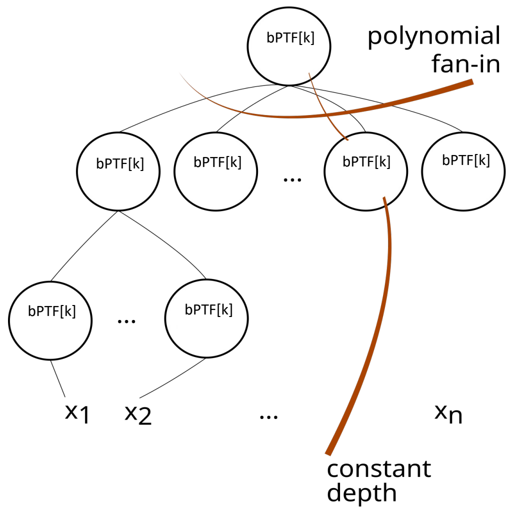
Definition ($\mathrm{bPTF}^0[k]$).

Constant-depth circuits with unbounded fan-in bPTF[k] gates defined as follows,

$$f_{Or}(x) = \begin{cases} P(x), & \sum_{i=0}^{n} x_i \le k \\ 1, & \sum_{i=0}^{n} x_i > k \end{cases}$$

with $P: F_2^n \to F_2$ a polynomial over $F_2 = \{0,1\}$.



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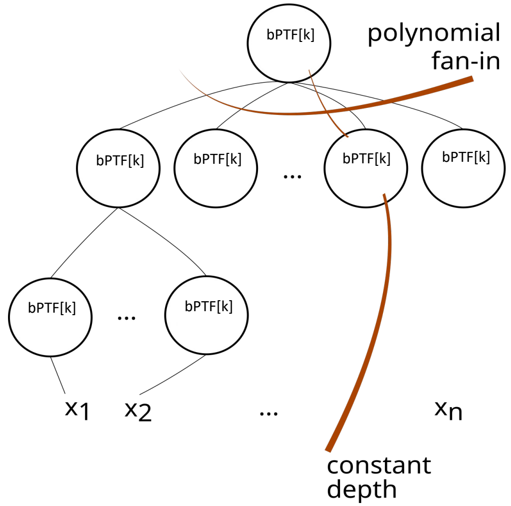
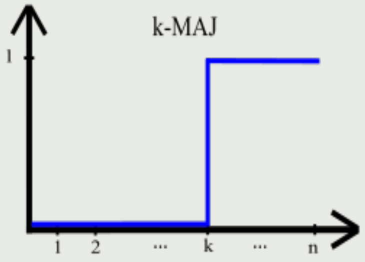


Example

$\mathrm{bPTF}^0[k]$ includes k-parameterized TH gates



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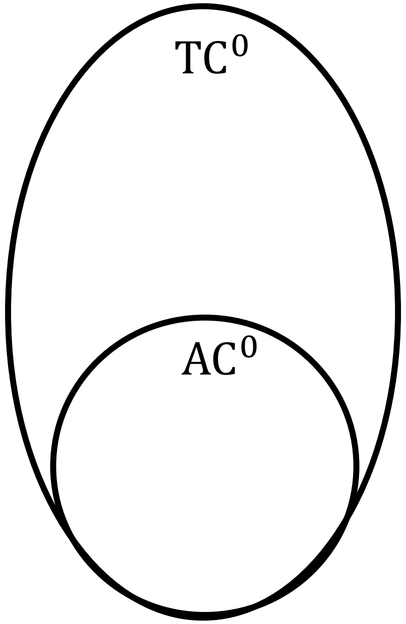

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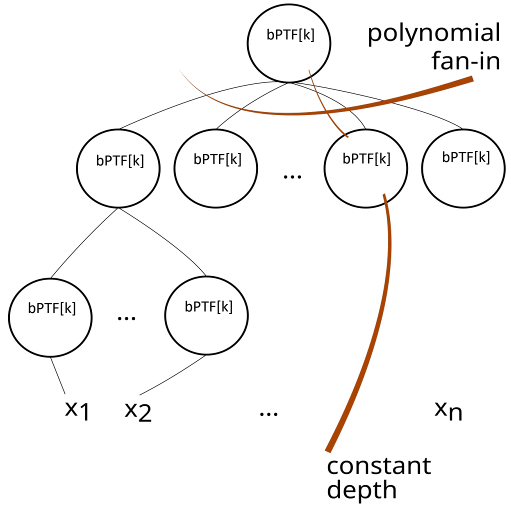

$\mathrm{AC}^0 = \mathrm{bPTF}^0[1]$

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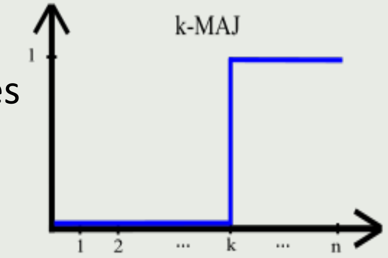
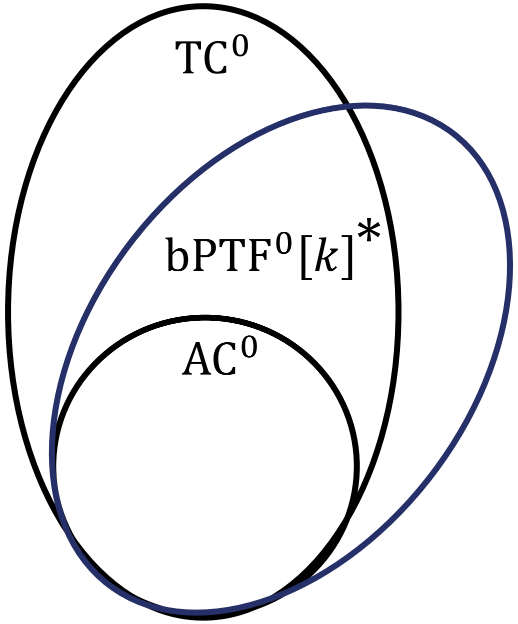


How powerfull are constant-depth quantum circuits?

- Alternatively can there exists a $\mathrm{bPTF}^0[k]$ circuits parameterized by k can interpolate between AC^0 and beyond TC^0.



Definition ($\mathrm{bPTF}^0[k]$).

Constant-depth circuits with unbounded fan-in bPTF[k] gates defined as follows,

$$f_{Or}(x) = \begin{cases} P(x), & \sum_{i=0}^{n} x_i \leq k \\ 1, & \sum_{i=0}^{n} x_i > k \end{cases}$$

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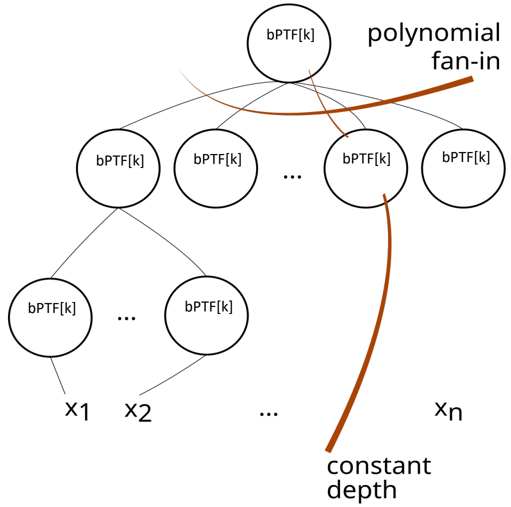

$$\mathrm{AC}^0 = \mathrm{bPTF}^0[1]$$

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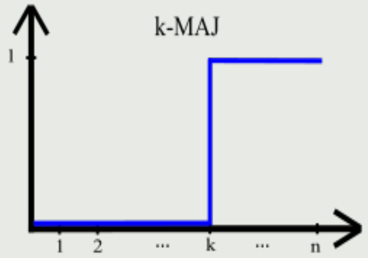

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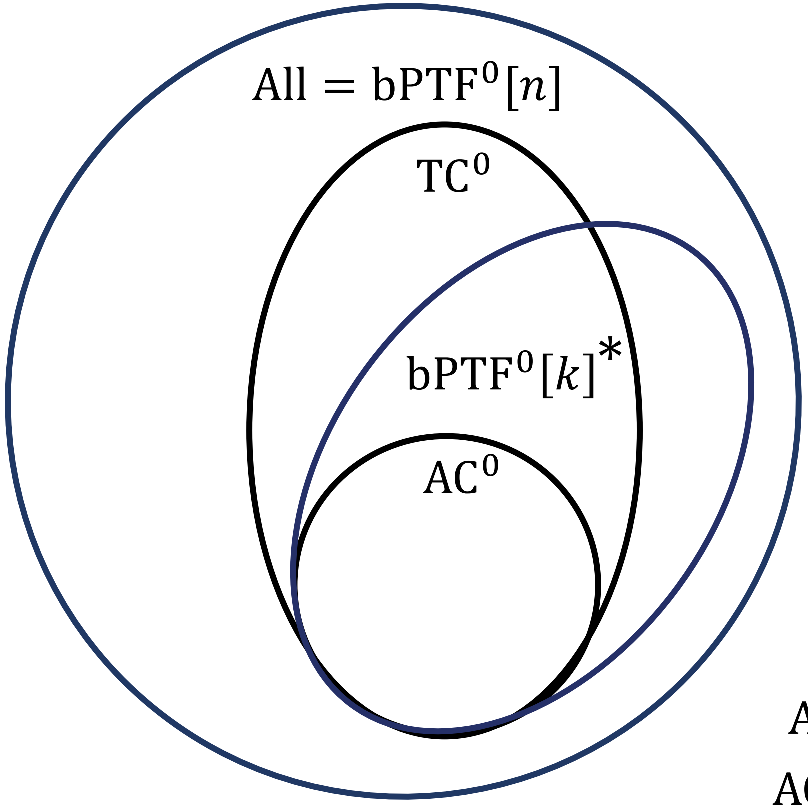

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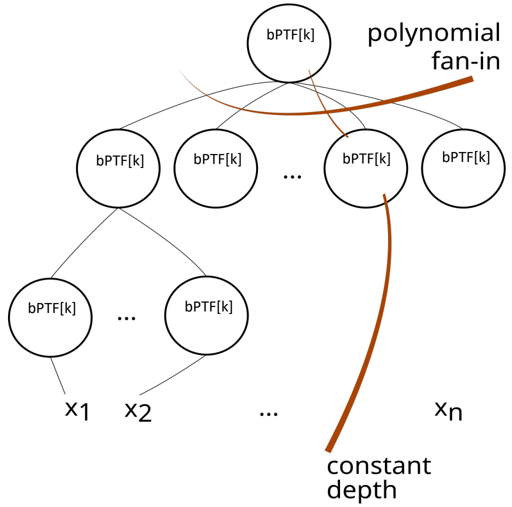

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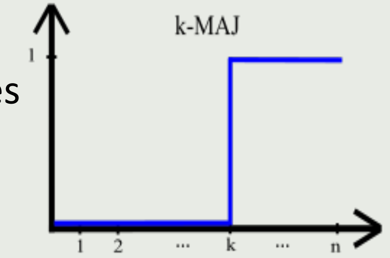

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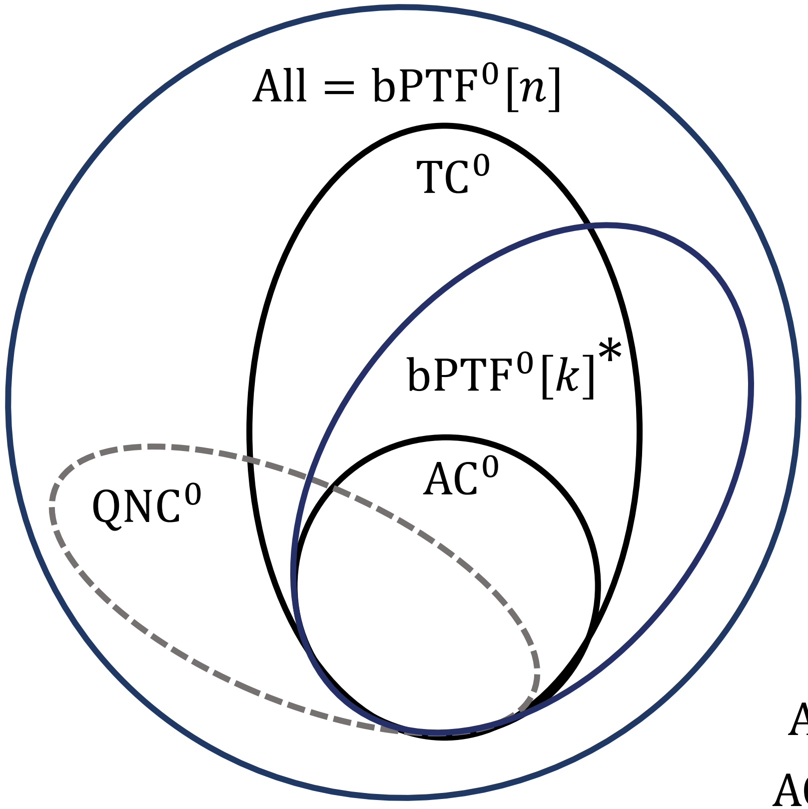

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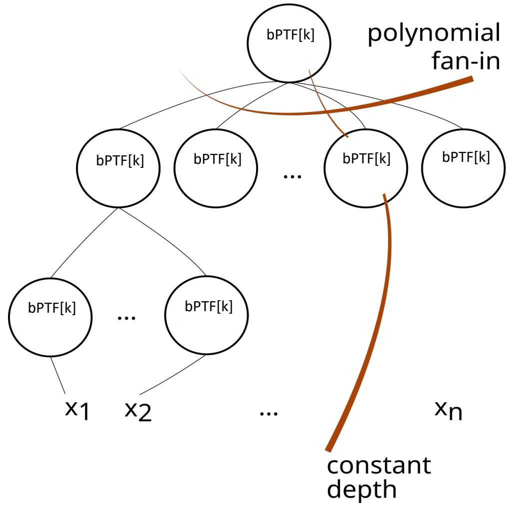

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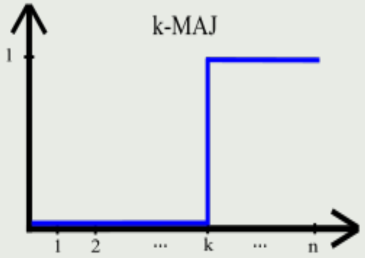
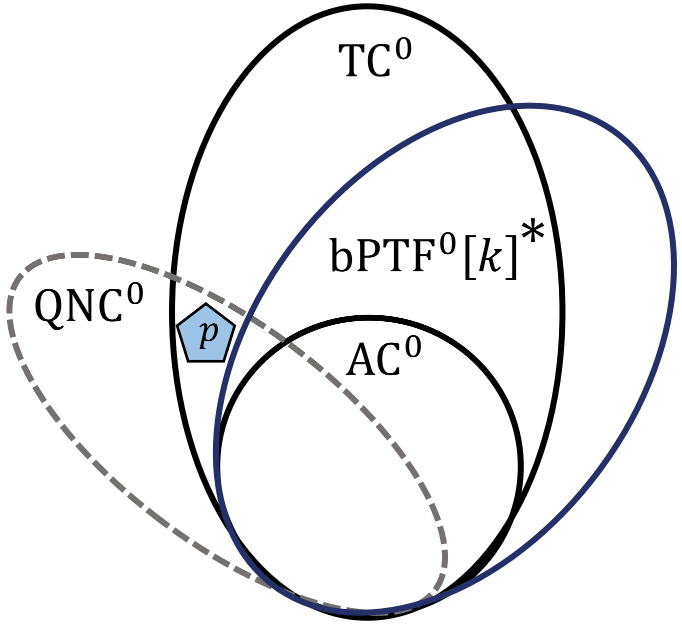


New Quantum-Classical unconditional separations



$\mathrm{QNC}^0 \not\subseteq \mathrm{bPTF}^0[\boldsymbol{n^{1/5d}}]$

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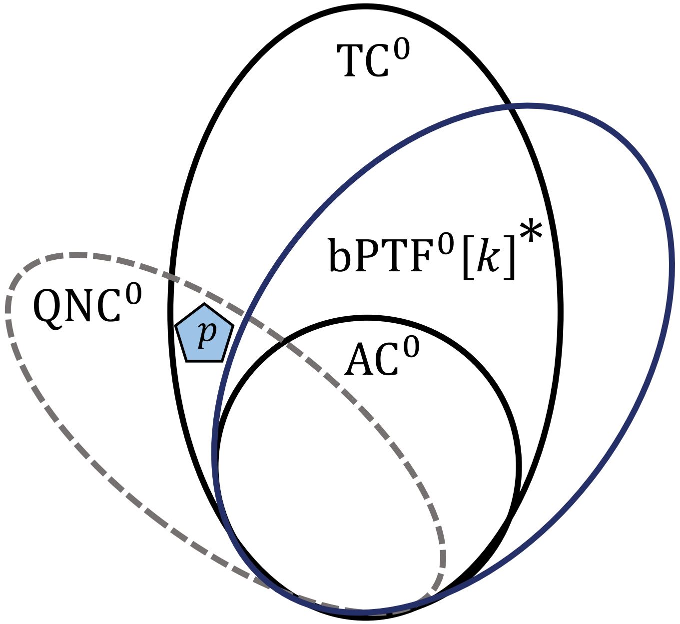
- We proved that **parallel quantum computation unconditionally outperforms** larger classical circuits classes, including biased Neural Networks.



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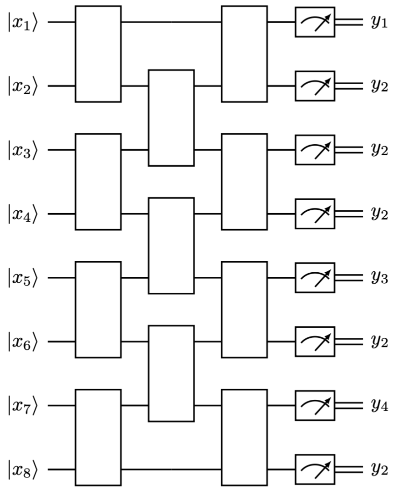

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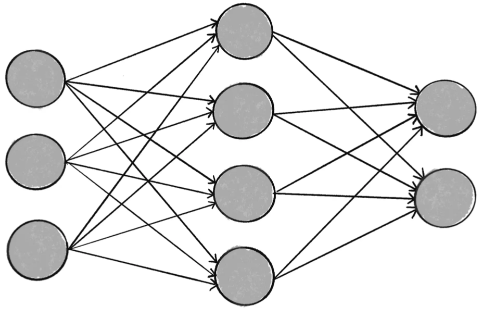

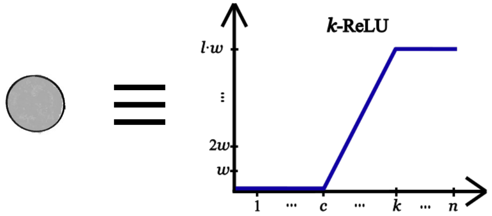

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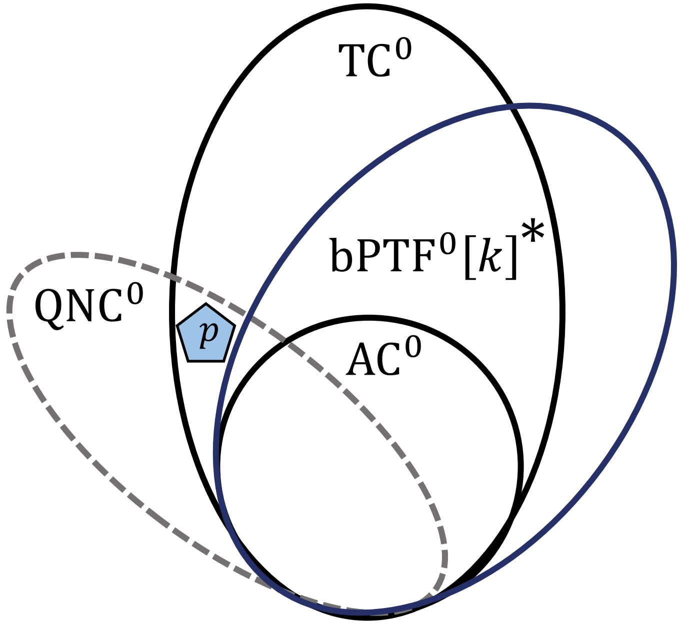

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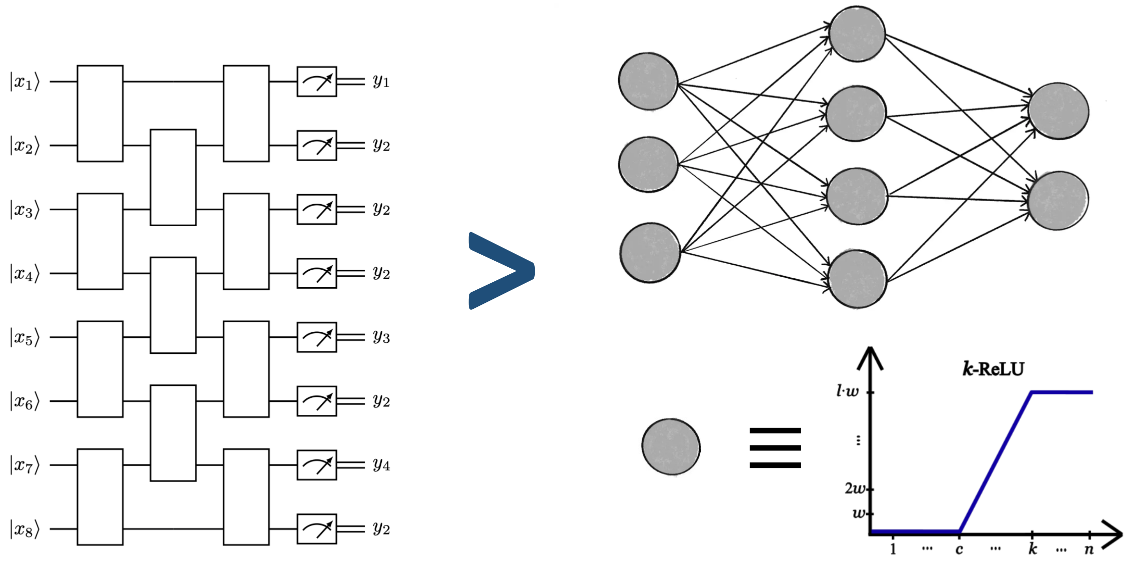
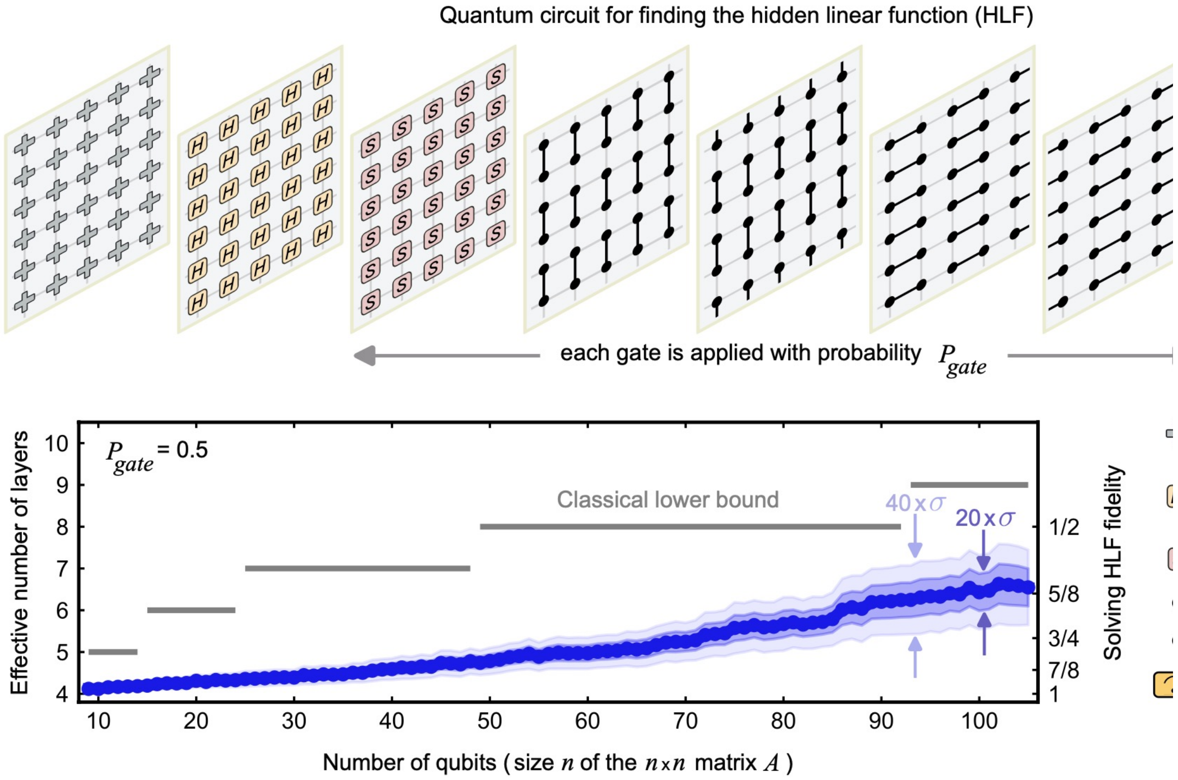


- This advantage **is robust to noise** and operates on **qudit quantum devices**.

Solving the Hidden Linear shift problem on quantum devices

This week, the Google team released a paper on the realization of HLF on their Willow chip.



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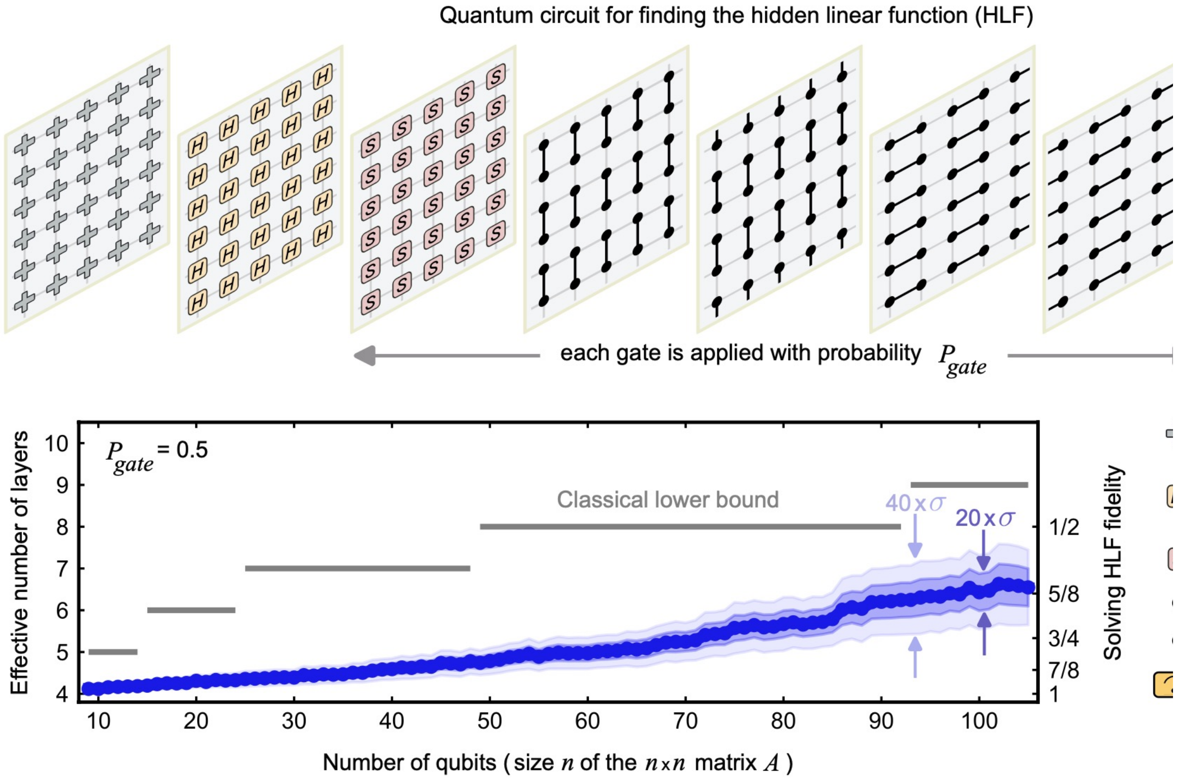
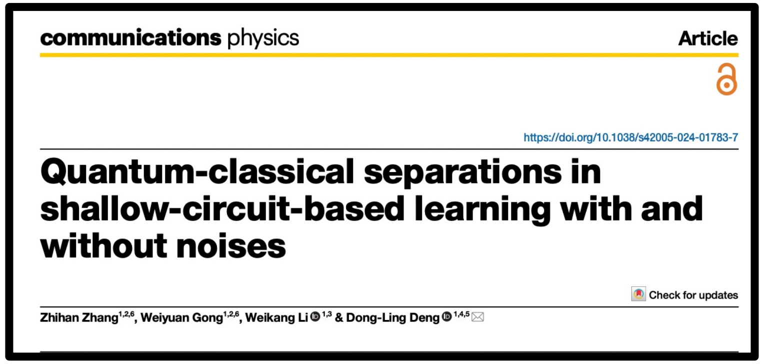


*If they could scale the number of qubits, they could realize our new quantum advantages.

New Practically Motivated Quantum-Classical unconditional separations

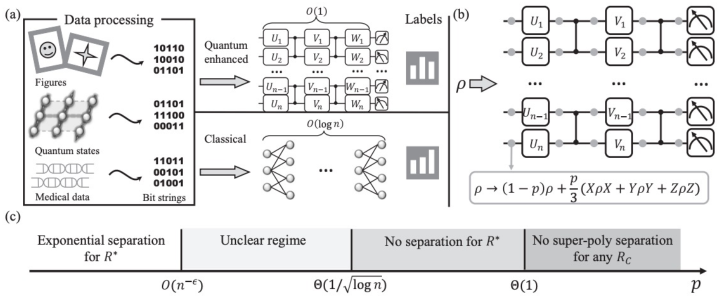

communications physics — Article

https://doi.org/10.1038/s42005-024-01783-7

Quantum-classical separations in shallow-circuit-based learning with and without noises

Check for updates

Zhihan Zhang[1,2,6], Weiyuan Gong[1,2,6], Weikang Li[1,3] & Dong-Ling Deng[1,4,5]



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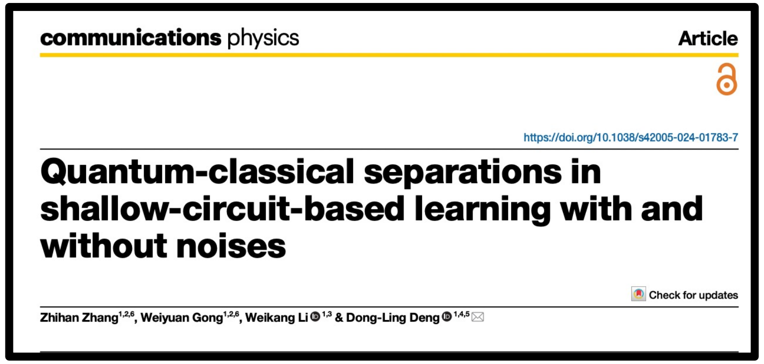
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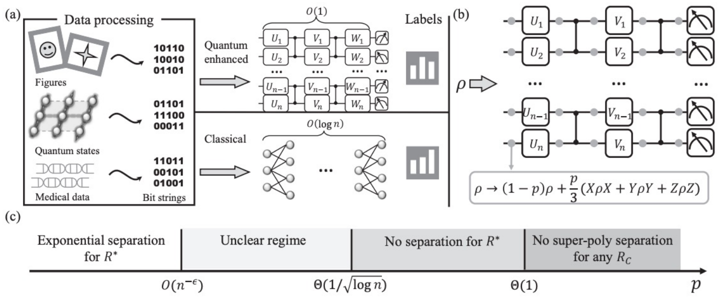
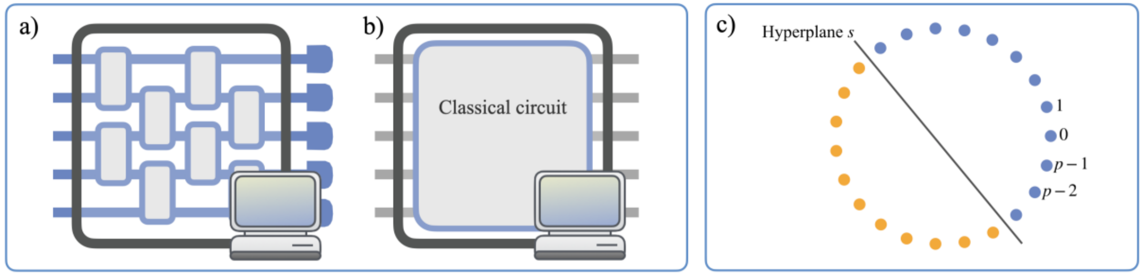



An unconditional distribution learning advantage with shallow quantum circuits

N. Pirnay,[1] S. Jerbi,[2] J.-P. Seifert,[1] and J. Eisert[2,3,4]

[1]*Electrical Engineering and Computer Science, Technische Universität Berlin, Berlin, 10587, Germany*
[2]*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*
[3]*Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany*
[4]*Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany*



The Quantum Benchmarking problem

Quantum Benchmarks

Quantum Benchmarks which test quantum devices should be:

- Algorithm agnostic

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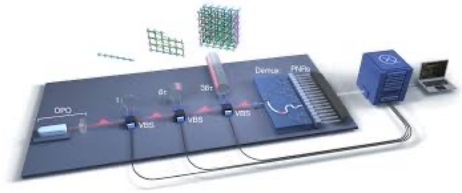

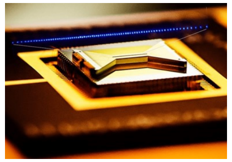

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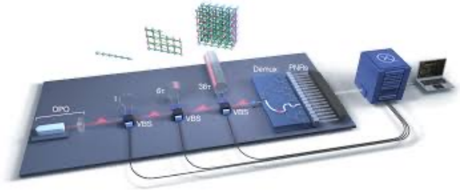
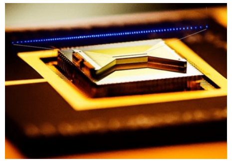

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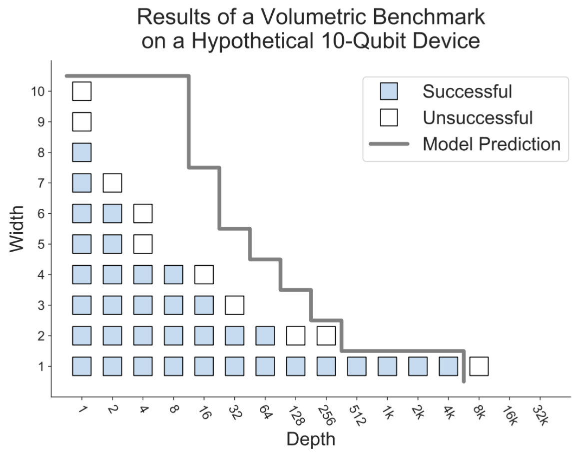

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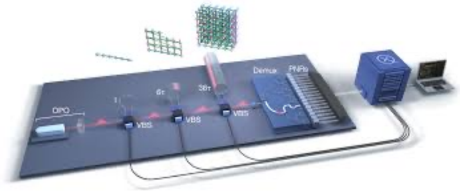

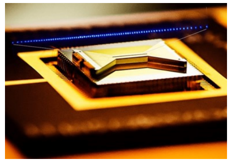

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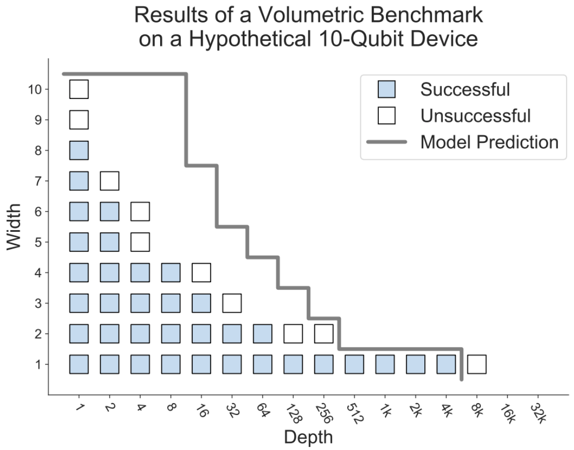

Misses to be predictive and scalable

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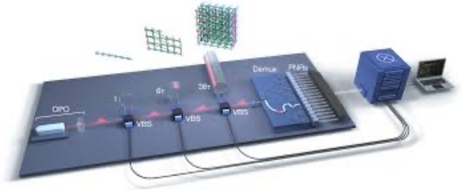

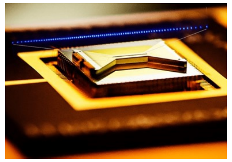

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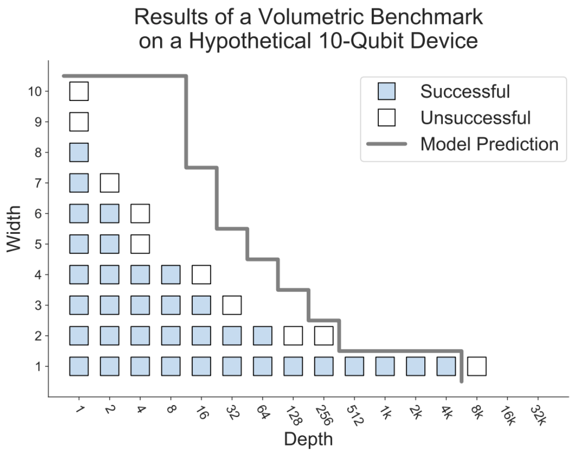
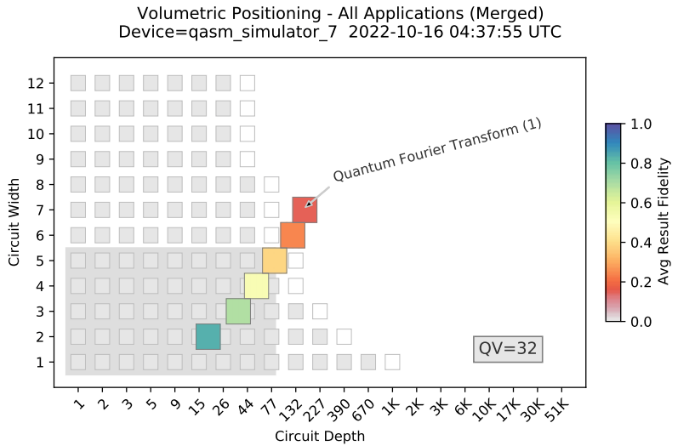


Misses to be predictive and scalable

Application-oriented benchmarks



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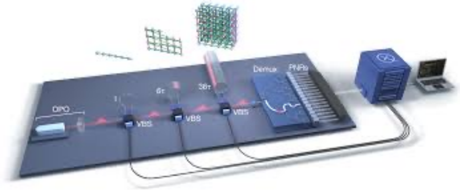

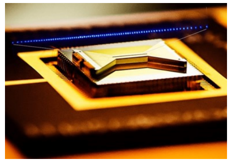

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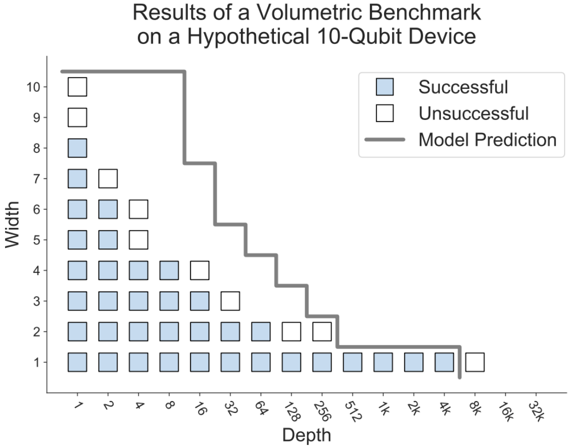

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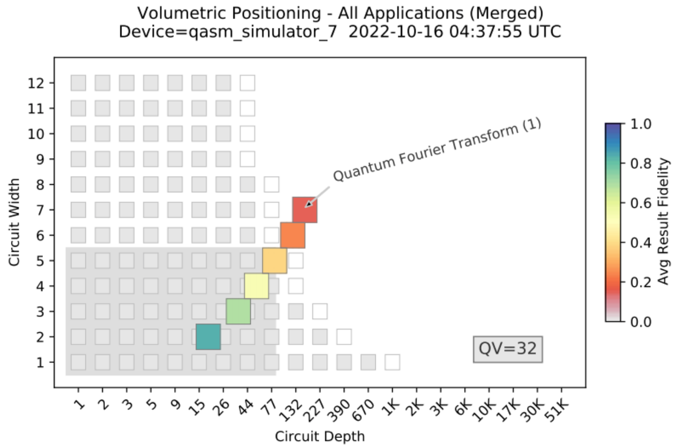

Misses to algorithm agnostic and predictive

Certifying the accuracy of quantum computers

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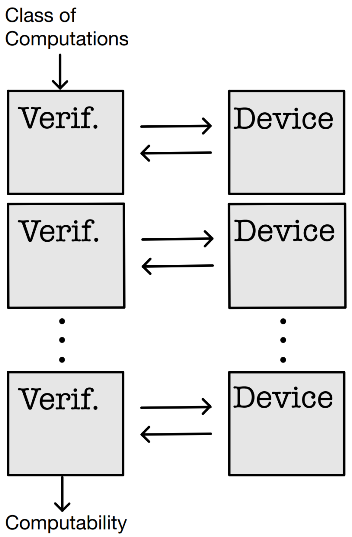

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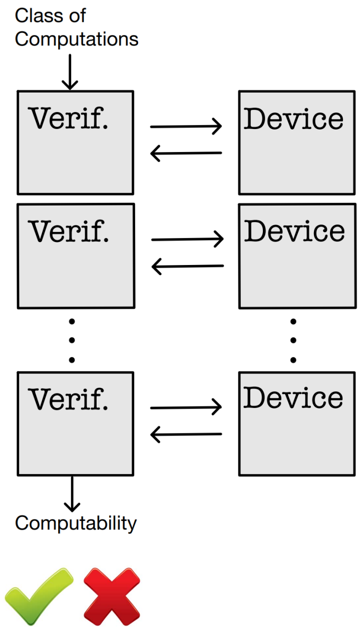

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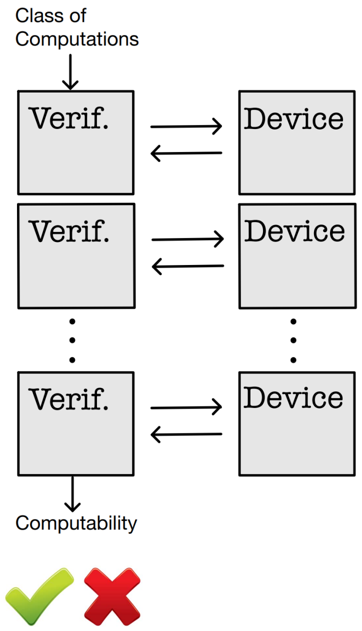

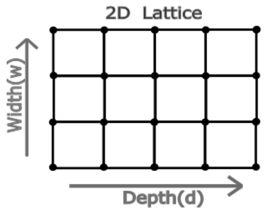

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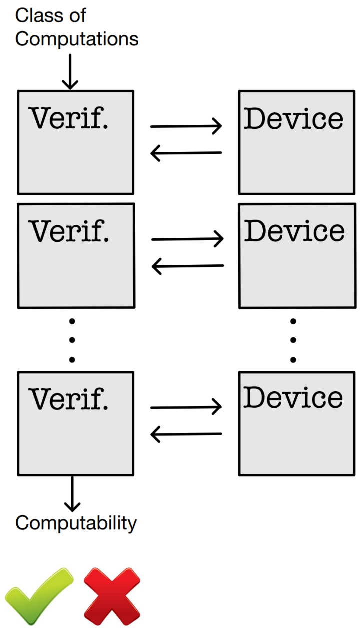

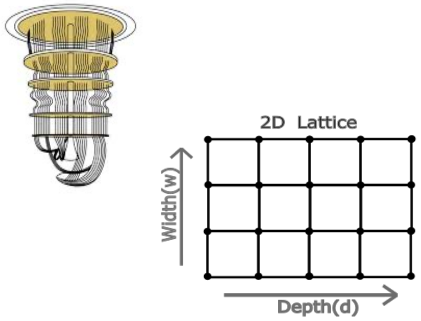

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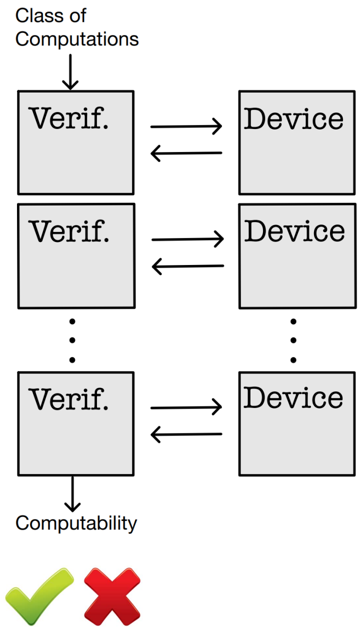

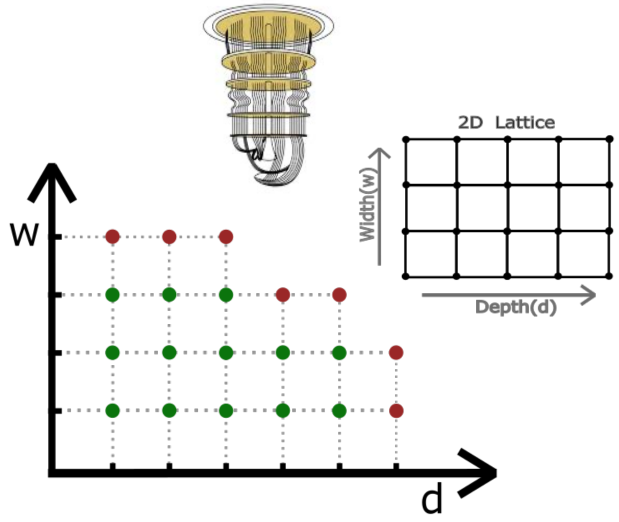

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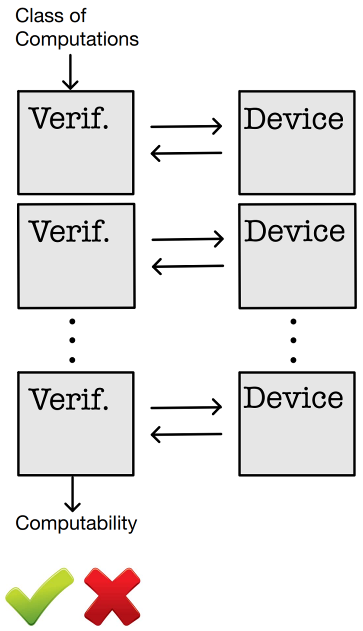
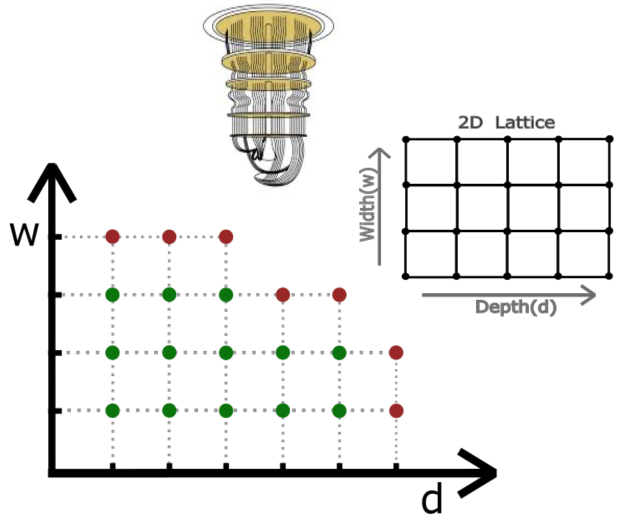
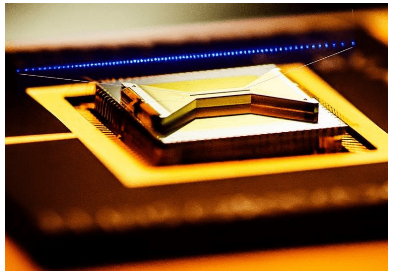




- This benchmark has already been used to test Quantinuum's H1 ion trap quantum processing unit.



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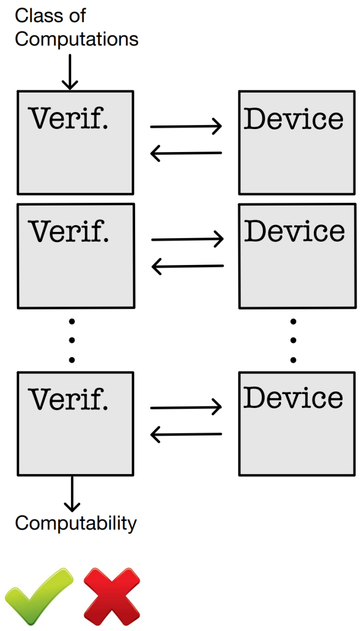

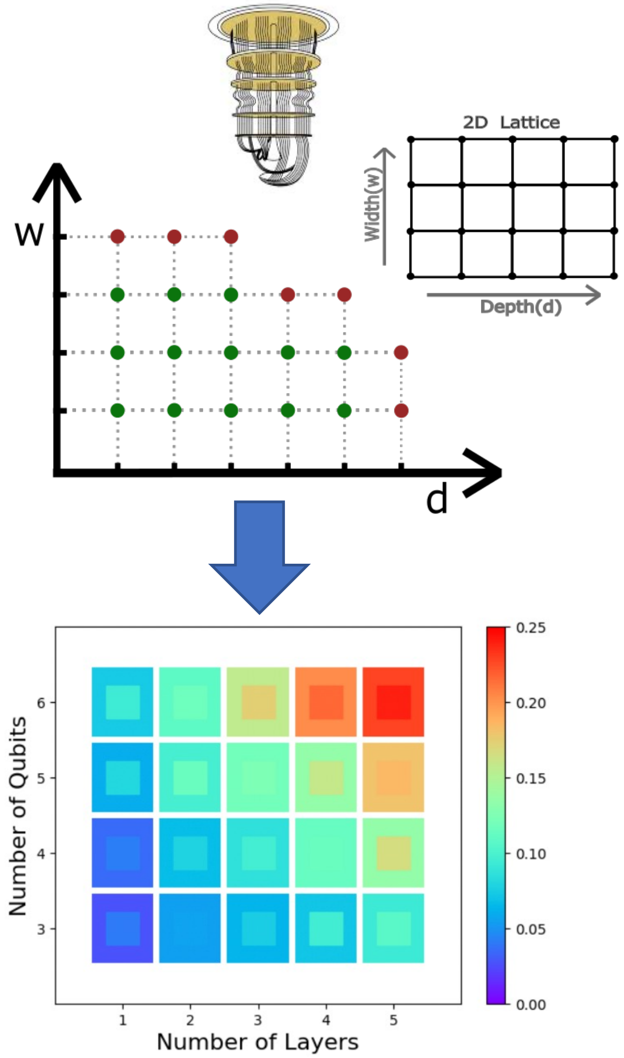

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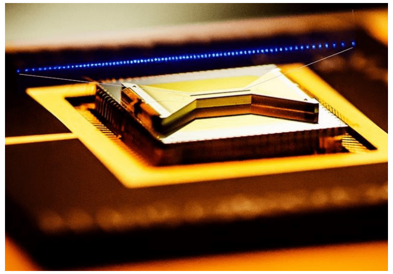
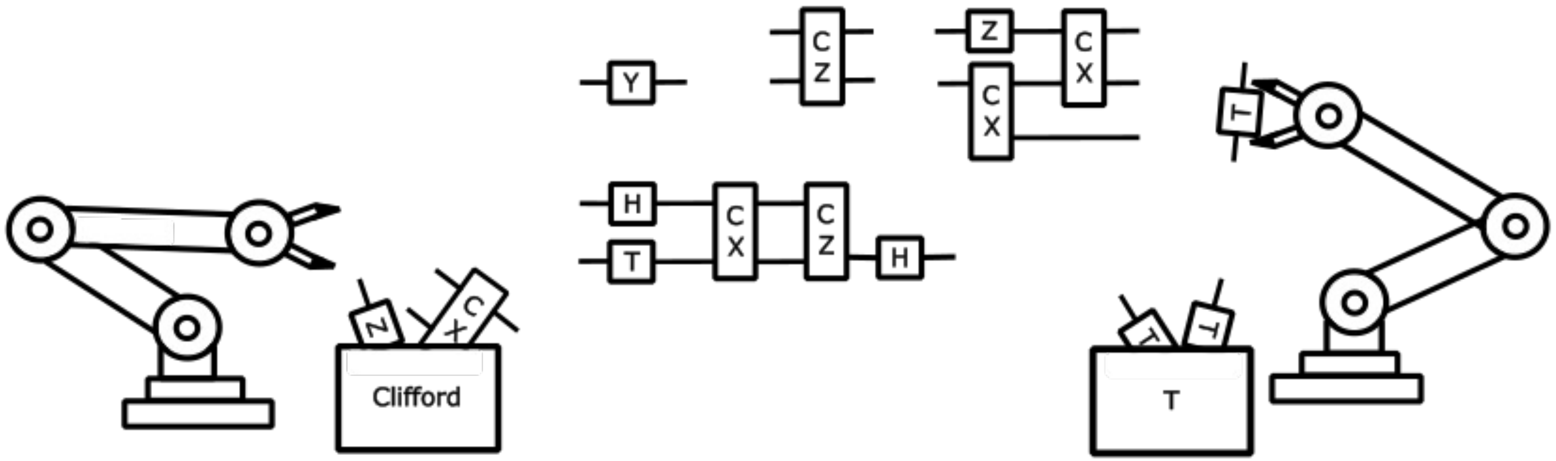
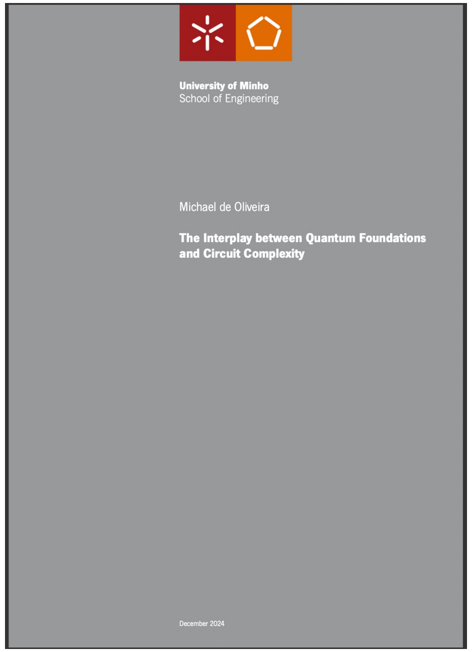


The circuit synthesis problem



The quest for quantum advantage

This work and its results gave origin to,


University of Minho
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Michael de Oliveira

The Interplay between Quantum Foundations and Circuit Complexity

December 2024

My PhD thesis

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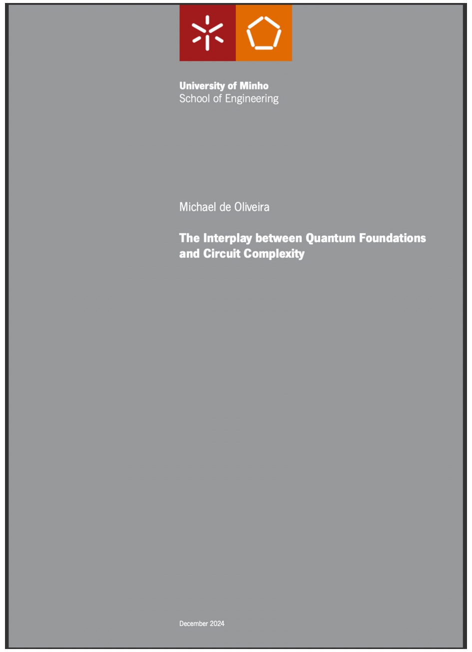
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arXiv:2212.03668v4 [quant-ph] 8 Apr 2024

Quantum advantage in temporally flat measurement-based quantum computation

Michael de Oliveira[1,2,3], Luís Soares Barbosa[1,2,3], and Ernesto F. Galvão[3,4]

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Several classes of quantum circuits have been shown to provide a quantum computational advantage under certain assumptions. The study of ever more restricted classes of quantum circuits capable of quantum advantage is motivated by possible simplifications in experimental demonstrations. In this paper we study the efficiency of measurement-based quantum computation with a completely flat temporal ordering of measurements. We propose new constructions for the deterministic computation of arbitrary Boolean functions, drawing on correlations present in multi-qubit Greenberger, Horne, and Zeilinger (GHZ) states. We characterize the necessary measurement complexity using the Clifford hierarchy, and also generally decrease the number of qubits needed with respect to previous constructions. In particular, we identify a family of Boolean functions for which deterministic evaluation using non-adaptive MBQC is possible, featuring quantum advantage in width and number of gates with respect to classical circuits.

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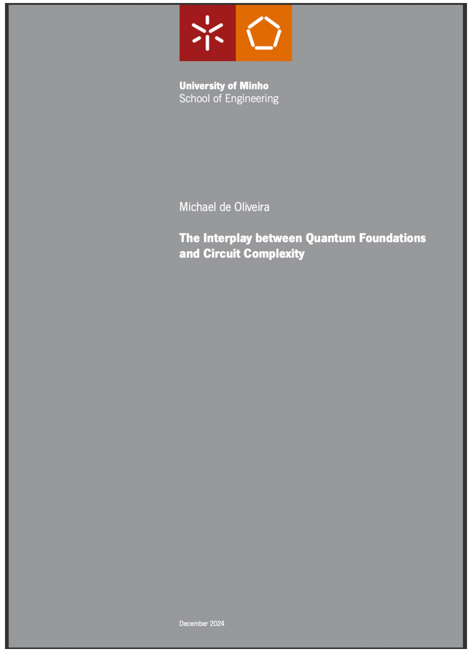
New synthesis techniques for shallow quantum circuits

The quest for quantum advantage

This work and its results gave origin to,



My PhD thesis

which is composed of

New synthesis techniques for shallow quantum circuits

A new quantum benchmarking protocol

The quest for quantum advantage

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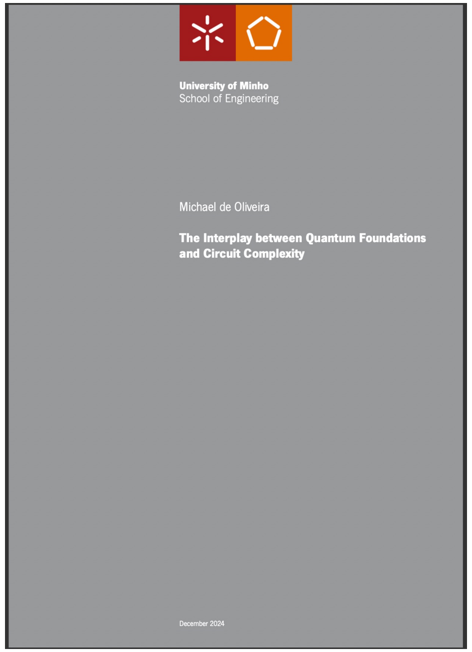
University of Minho
School of Engineering

Michael de Oliveira

The Interplay between Quantum Foundations and Circuit Complexity

December 2024

My PhD thesis

which is composed of


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Michael de Oliveira, Luís Soares Barbosa, and Ernesto F. Galvão

arXiv:2212.03668v4 [quant-ph] 8 Apr 2024

New synthesis techniques for shallow quantum circuits


Heuristic-free Verification-inspired Quantum Benchmarking

Johannes Frank, Elham Kashefi, Dominik Leichtle, Michael de Oliveira

arXiv:2404.10739v1 [quant-ph] 16 Apr 2024

A new quantum benchmarking protocol


Unconditional advantage of noisy qudit quantum circuits over biased threshold circuits in constant depth

Michael de Oliveira, Sathyawageeswar Subramanian, Leandro Mendes, and Min-Hsiu Hsieh


The Power of Shallow-depth Toffoli and Qudit Quantum Circuits

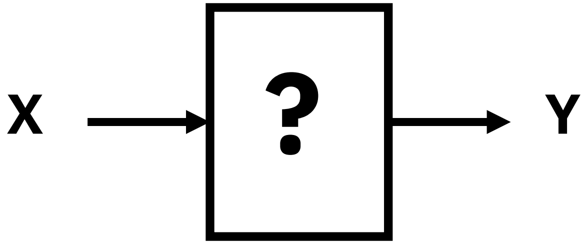
ALEX B. GRILO, ELHAM KASHEFI, DAMIAN MARKHAM, MICHAEL DE OLIVEIRA

Unconditional quantum advantages with shallow depth circuits

Thank you!

@IBM - A New Quantum Learning Algorithm

Understand how hard it is to learn an unknown process:



$$? : \{0,1\}^n \to \{0,1\}$$

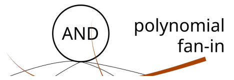
Focus:

– Sample complexity
– Accuracy of the learned hypothesis
– Run-time

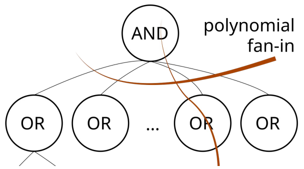
Learning arbitrary Boolean functions is an extremely hard problem!

? :

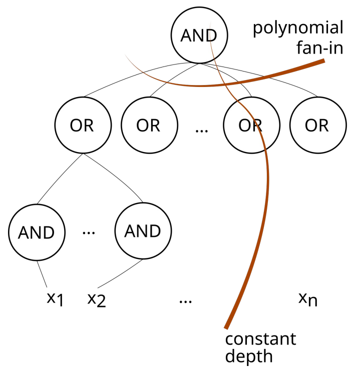
Depth 1



Depth 2



Depth 3



We present a novel, state-of-the-art quantum learning algorithm for PAC learning depth-3 circuits.