Quantum Machine Learning

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Introduction

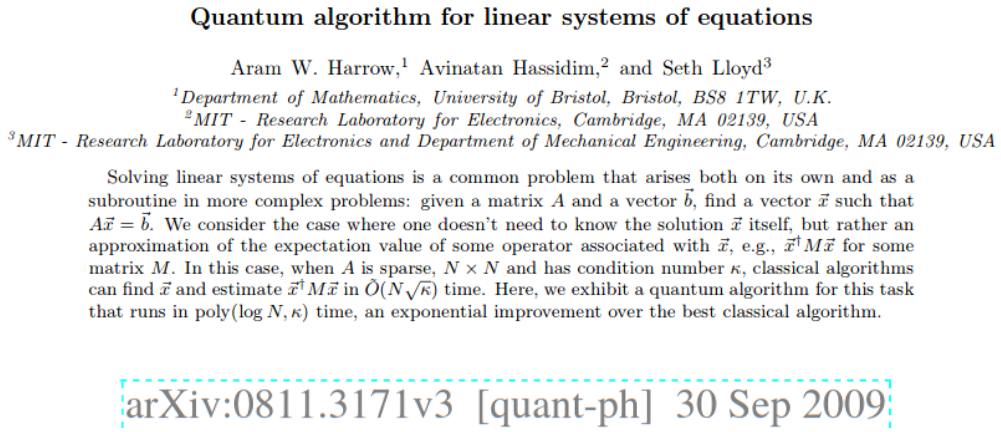
- One of the 3 main axes so far identified for the QC2I project.
  - general idea: explore QML application in the areas where ML and AI are currently used in Particle, Nuclear Physics and Astrophysics;
- in our communities there are already several groups working on this same program (e.g. the CERN QTI)
  - already a lot of results and publications;
- we are not (that) late but it is a timely moment to start contributing
  - some preliminary work ongoing at LLR and IJClab;
  - we know some other members of QC2I have ideas/expertise/publications;
- here the idea is to give few inputs mostly to settle the context and to trigger discussion, collect ideas, interests, etc.

Machine Learning

- In recent years ML - DL in particular - have made enormous progresses
  - wide range of app. in industry and in research;
  - DNN: efficiently handle high dim/vol data;
- widely used in HEP
  - since '90, real explosion in the 2010s (CHEP2021 ~35/212 ML papers);
  - mostly BDT and NN;
  - evts selection, particles/jets class., reco., tracking, fast simulation…
- in Nuclear Physics
  - rather new approach;
  - e.g.: use NN as extrapolation tools for ab-initio methods;
  - predict masses, spectrum, deformations,…;
  - extend models to nuclei in regions that cannot be experimentally explored.

Quantum Machine Learning

- a lot of hype since the break-through algorithm of HHL
  - "(one of) the most convincing reasons to build quantum computers";
  - opens QC to a huge range of applications with potential exp. speedups;
- a great number of HHL-like "full" QML algorithms have been proposed
  - the speedup of such algorithms in ML problems has several caveats;
  - require high-depth q. circ. (thus large noiseless QC) and possibly qRAM;
- (in most cases) not for the NISQ era
  - still they are very interesting to study;
  - "real life" applications are today mostly oriented on Hybrid Quantum Classical ML …
  - … or Quantum Annealing.



Quantum algorithm for linear systems of equations

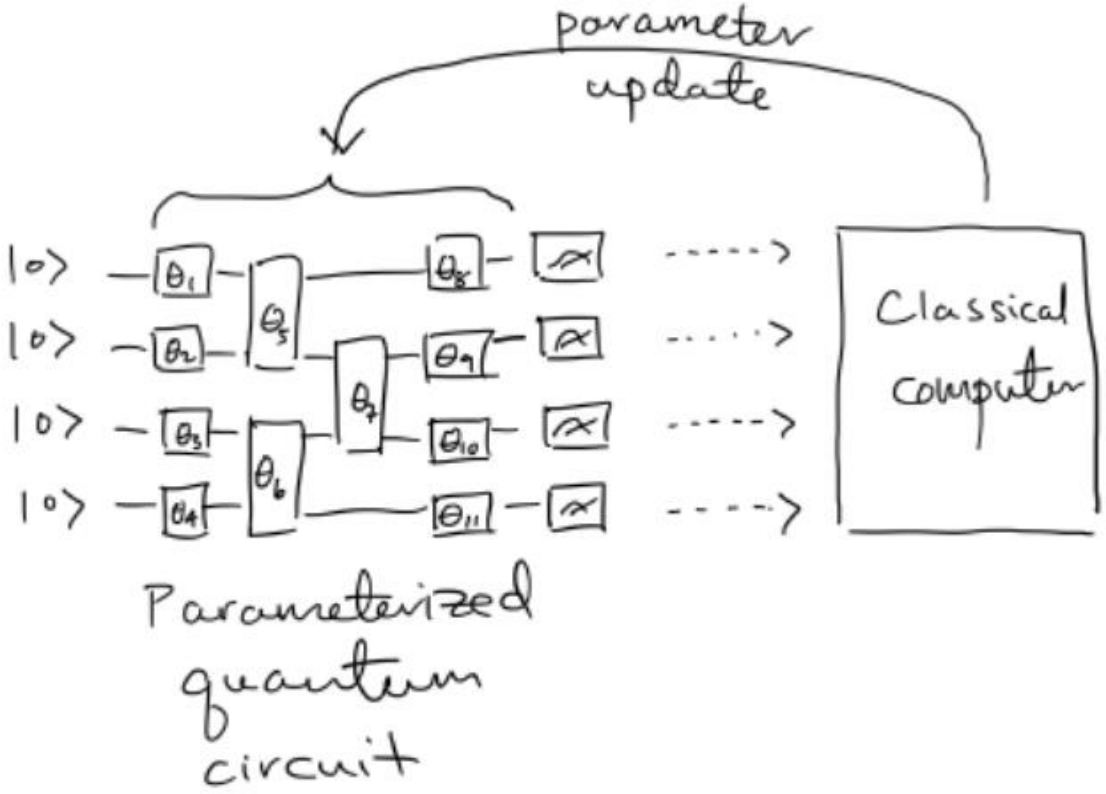
Aram W. Harrow,[1] Avinatan Hassidim,[2] and Seth Lloyd[3]

[1]*Department of Mathematics, University of Bristol, Bristol, BS8 1TW, U.K.*
[2]*MIT - Research Laboratory for Electronics, Cambridge, MA 02139, USA*
[3]*MIT - Research Laboratory for Electronics and Department of Mechanical Engineering, Cambridge, MA 02139, USA*

Solving linear systems of equations is a common problem that arises both on its own and as a subroutine in more complex problems: given a matrix A and a vector $\vec{b}$, find a vector $\vec{x}$ such that $A\vec{x} = \vec{b}$. We consider the case where one doesn't need to know the solution $\vec{x}$ itself, but rather an approximation of the expectation value of some operator associated with $\vec{x}$, e.g., $\vec{x}^\dagger M\vec{x}$ for some matrix M. In this case, when A is sparse, $N \times N$ and has condition number κ, classical algorithms can find $\vec{x}$ and estimate $\vec{x}^\dagger M\vec{x}$ in $\tilde{O}(N\sqrt{\kappa})$ time. Here, we exhibit a quantum algorithm for this task that runs in poly$(\log N, \kappa)$ time, an exponential improvement over the best classical algorithm.

arXiv:0811.3171v3 [quant-ph] 30 Sep 2009

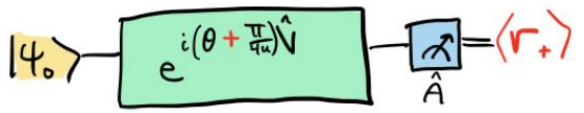
Hybrid Classical-Quantum ML

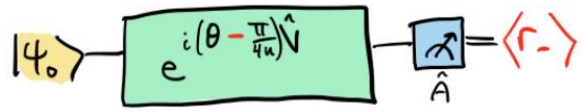


Circ. with parametric gates (e.g. rotation) used as (one part of a) model.

Model is evaluated by a QC on the training set then optimization is made classically.

In order to make gradient descent we need to compute the gradient which can be done with the "parameter shift rule".





Gradient: $\nabla_\theta\langle\hat{A}\rangle = u[\langle r_+\rangle - \langle r_-\rangle]$

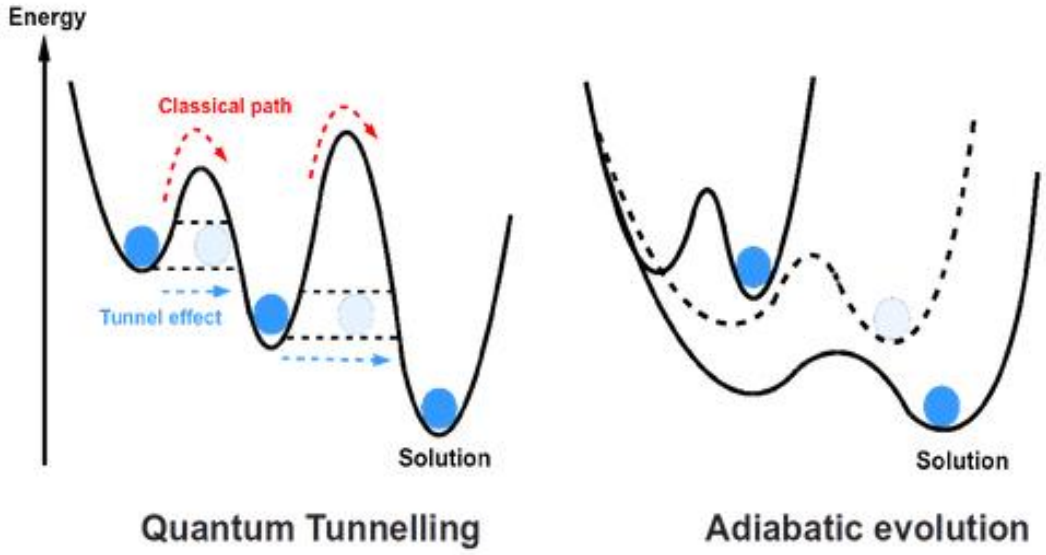
Quantum Annealing

We can express a problem in terms of the minimization of a QUBO.

$$O(a;b;q) = \sum_{i=1}^{N} a_i q_i + \sum_{i}^{N} \sum_{j}^{N} b_{ij} q_i q_j \quad q_i \in \{0,1\}$$

On a QA we can start from a "free" system on the ground state and slowly "activate" the interactions defining the QUBO. The final state will tell us the solution of the QUBO.

modulo: noise, statistics, mapping to actual architecture, etc…



$$H = (1-s)H_0 + sH_1$$

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HEP Applications

Quantum Machine Learning in High Energy Physics

Wen Guan[1], Gabriel Perdue[2], Arthur Pesah[3], Maria Schuld[4], Koji Terashi[5], Sofia Vallecorsa[6], Jean-Roch Vlimant[7]

arXiv:2005.08582v2 [quant-ph] 19 Oct 2020

Simulation of Collective Neutrino Oscillations on a Quantum Computer

Benjamin Hall,[1] Alessandro Roggero,[2,3] Alessandro Baroni,[4] and Joseph Carlson[4]

arXiv:2102.12556v1 [quant-ph] 24 Feb 2021

A quantum algorithm for the classification of Supersymmetric top quark events

Pedrame Bargassa[1,2], Timothée Cabos[3], Samuele Cavinato[4,5], Artur Cordeiro Oudot Choi[3], Timothée Hessel[3]

arXiv:2106.00051v2 [quant-ph] 2 Jun 2021

Particle Track Reconstruction with Quantum Algorithms

Cenk Tüysüz[1,2,*], *Federico* Carminati[3], *Bilge* Demirköz[1], *Daniel* Dobos[4,6], *Fabio* Fracas[3], *Kristiane* Novotny[4], *Karolos* Potamianos[4,5], *Sofia* Vallecorsa[3], and *Jean-Roch* Vlimant[7]

arXiv:2003.08126v1 [quant-ph] 18 Mar 2020

Dual-Parameterized Quantum Circuit GAN Model in High Energy Physics

Su Yeon Chang[1,2,*], *Steven* Herbert[3,4,**], *Sofia* Vallecorsa[1,***], *Elías F.* Combarro[5], and *Ross* Duncan[3,6,7]

arXiv:2103.15470v1 [quant-ph] 29 Mar 2021

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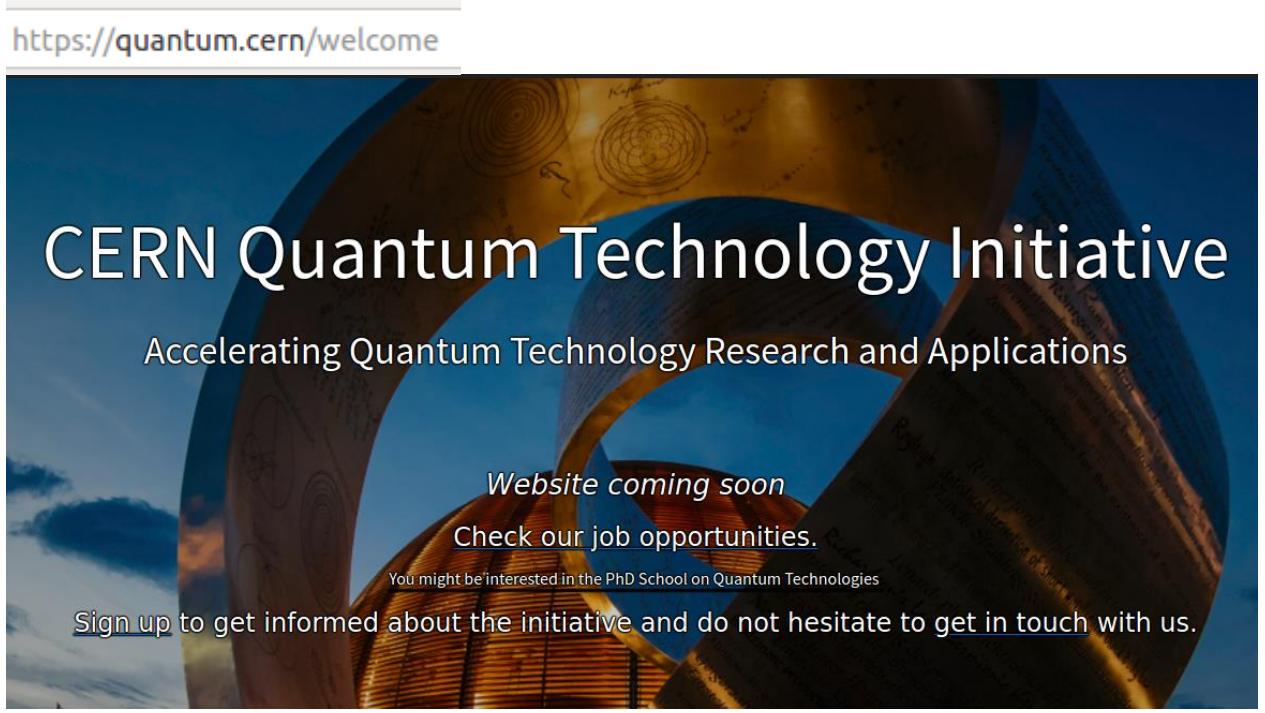
HEP Initiatives

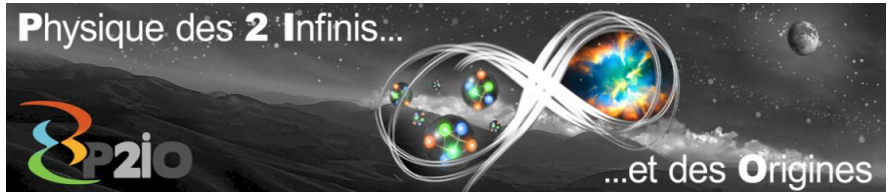


For the computing part much focus on QML.

We already took contacts with this group and they would be happy to collaborate with us.

TuToQML project

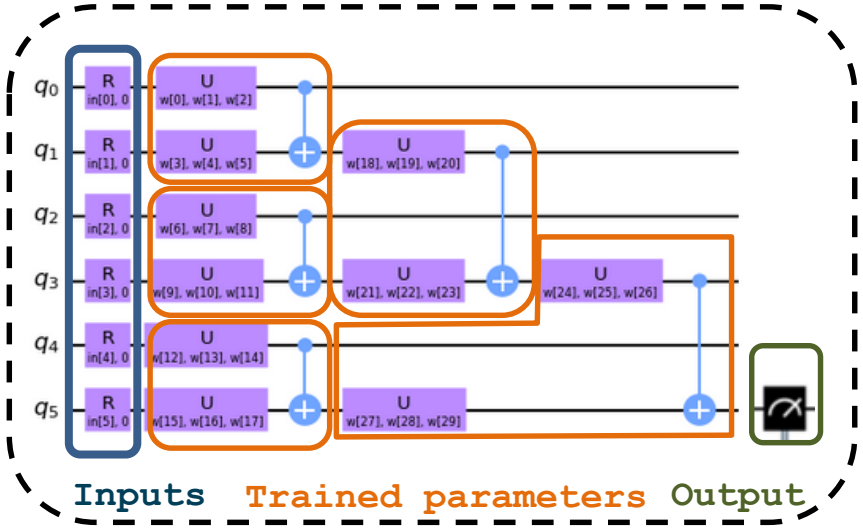
2 years postdoc grant IJClab/LLR (recruiting now…)

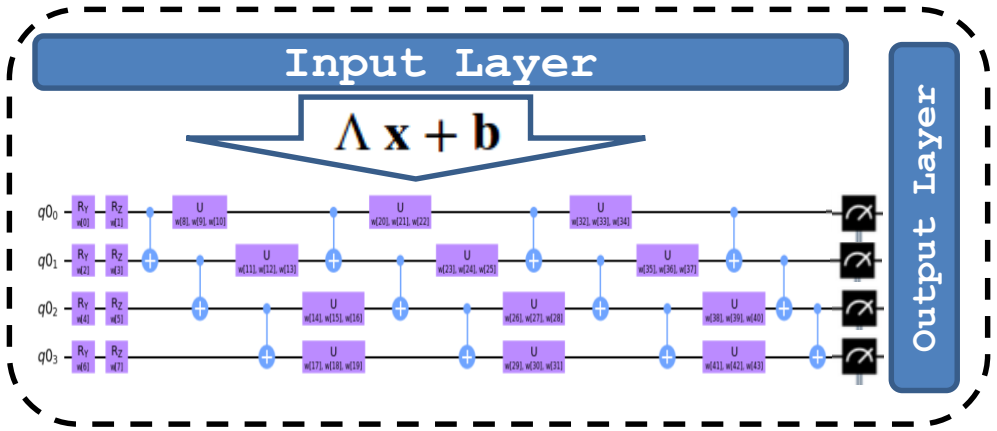


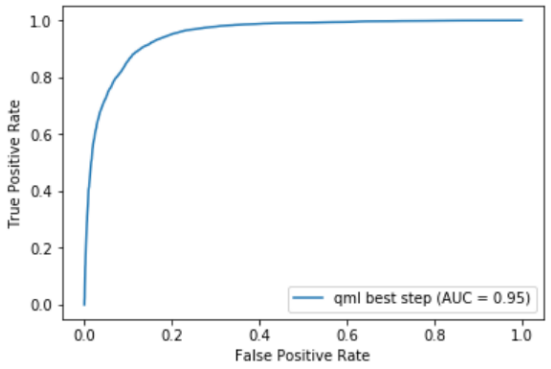
Some Work Ongoing

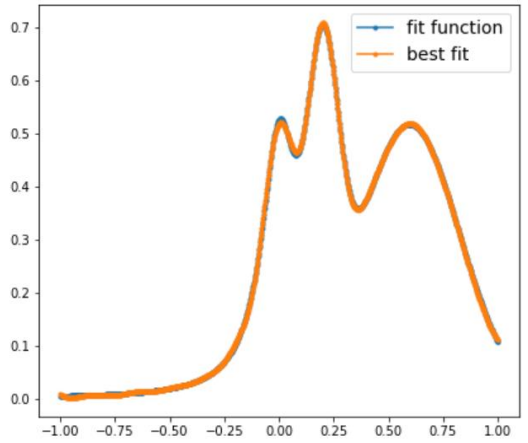
Testing different more or less standard architectures with simple regression and classification tasks as well as evts classification problems.

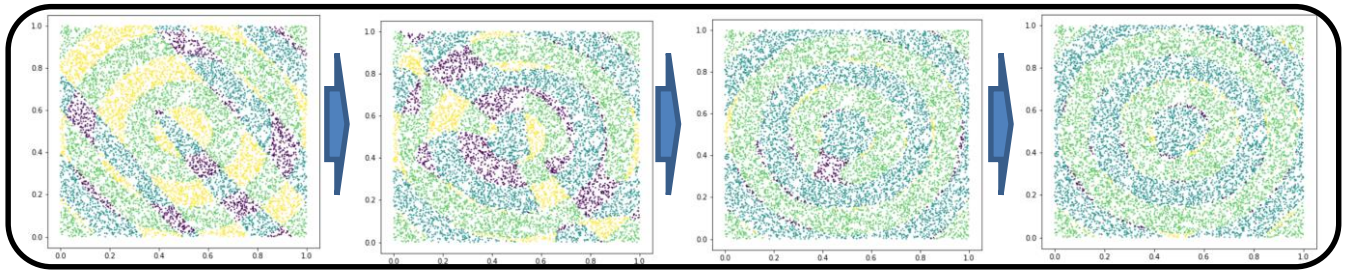
Not that far from what CERN QTI is doing in this moment.











Conclusions

- QML has been hyped since its "birth" with the HHL algo
  - opens QC to a huge range of applications;
  - NISQ-compliant QML: hybrid QML and q. annealing
    - starting point for "new" communities testing apps (like us);
    - this does not mean that "full" QML algos are of no interest…;
- in HEP there is already a good number of people exploring QML
  - on our side we took contact with the CERN group and started some explorative work on our own;
  - QC2I project has regular QML meeting (~ 1 month) since 1/2021;
- We are not that late and there is a lot of room for contribution
  - some of you already put forward ideas and in some cases already worked actively on QML;
  - so… the mic is yours.