

Case study of Scalable Quantum Simulation of Molecular Energies

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1 Introduction

“Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.” Richard Feynman’s words are as true today as when he spoke them almost forty years ago. And it is this opinion of Feynman among others which prompted the enormous effort that has been expended on the development of quantum computing since then. The paper ‘Scalable Quantum Simulation of Molecular Energies’ by O’Malley et al. is evidence of just how far the technology has come in this time, and indicates what we might expect from superconducting quantum computing technologies in the future.

Simulation of physical systems is one of the most crucial practical applications of computation by far. For example, buildings are engineered in a safe and cost efficient way through the application of finite element analysis and modeling. The field of aeronautics relies heavily on computational fluid dynamics simulations. And even nuclear weapons systems are tested by exhaustive computational modeling.

However, even in light of its phenomenally far-reaching success in almost all areas of modern science and engineering, classical computation still has its limitations. When it comes to simulating microscopic systems, classical techniques require significant computational overhead which scales to unreasonable proportions with increasing system size. In quantum computational chemistry simulations, each subatomic orbital and their interactions needs to be considered to achieve an accurate and realistic simulation of the microscopic system. Since the state of one orbital can be affected by all of the others, an exponential number of states in the basis of molecular orbitals needs to be accounted for. Problems of this type are classified to be ‘many-body’ problems. No matter how far apart two orbitals are, their quantum states cannot be described independently, the repeated interactions between particles create quantum correlations, this phenomenon is known as entanglement.

A radically different computing paradigm is then employed to combat this problem, that is quantum computation. It harnesses the principles of quantum mechanics, hence solves these classically intractable problems of simulation more accurately, faster, with a more fine-grained simulation.

The amount of information needed to describe interactions in a quantum system would quickly fill up the memory of a classical computer, instead, a quantum computer can do tasks of this nature efficiently through the use of quantum bits, or qubits, for information storage and computation [6]. Since the classical storage unit ‘bit’ is binary system based on strings of 0s and 1s, but a quantum computer would encode them into two distinguishable quantum states, and one qubit can represent multiple states at once in the form of the quantum phenomenon of ‘superposition’. Similarly, if we perform a search algorithm on a classical string, the enumerate steps would be the number of bits within this string. Comparably, our processing step will reduce a lot more as we only need to compute once in a quantum processor.

2 History

Molecules are composed of collections of atoms, and the units that make up an atom are electrons and the atomic nucleus. When we consider the atomic energy then we must take into account both electron-nuclei and electron-electron interactions. The molecular energy consists of interactions between multiple atoms, and interactions between electrons from different nuclei. Molecular energy can be pictured as a large package that contains many small balls, and the sum of the energy of their collisions is the sum of interactions between atoms. Obviously, it demands massive computation to find out the package energy as it contains a huge amount of particles. Therefore, some approximations need to be made to simplify our model, which necessitates the introduction of molecular mechanics.

Molecular mechanics models molecular systems using force fields in classical mechanics. Three approximations were made to reduce the computational complexity. Each atom is simulated as one particle; each particle has their designated attributes including radius, Polaris ability and net charge; and interactions are treated as springs with an equilibrium distance same as bond length. Essentially this theory simulates every element of the molecular system as if it were fixed particles connected by strings, which hugely reduces the computational complexity.

The renormalisation group is a theory which also enables a reduction in the computational power needed for accurate simulations. A simple scenario is to calculate the resistance force of an iron ball in a glass of water. We can simply simulate every water molecule in the glass by using the real size of a single water molecule as one parameter - the sizes of the molecules can easily be another 1000 parameters as they can be irregular and difficult to describe. Forces from multiple directions of the iron ball could be another 1000 parameters. Inputting all parameters, modelling an iron ball and simulating 10^{26} water molecules and their interactions can give the resistance force.

Let's say we have a supercomputer that allows for a tremendous amount of data processing and the result that this simulation gives coincides with the experimental data to within an extremely high degree of accuracy.

But what if we want to reduce the computational complexity? One solution is to reduce the number of water molecules simulated, which is feasible given the relative much larger size of the iron ball. To make up for the loss in number of molecules, the rest if the parameters can be adapted. Whereby we can manipulate the parameters and the simulation gives slightly different solutions, but the overall trend is still the same as before. The computation complexity can still be compressed. We can repeat the process of reducing the number of molecules and adjusting the parameters and still generate acceptable solutions. This process is known as renormalisation group, and the results that this model generates are called low energy effective theory, in which the system size is reduced but the results are still accurate.

We now return to the theory of molecular mechanics, it is not exactly accurate since it is restricted by parameters of equations, i.e. different force fields for different atoms. A similar and perhaps more comprehensible explanation can be made from the theory of renormalisation group. While decreasing the parameters of calculation and reducing computation time, the accuracy of the result is decreasing as well. Molecular mechanics does the same for force fields and interactions inside the atom.

Overall, the work on simulating molecular energies with classical methods is a trade off between precision and cost. Quantum simulation is able to encapsulate all the relevant information of the system, and can simulate efficiently and with high accuracy.

3 Scientific Background

The building blocks of any quantum computing process may be considered to be qubits. A qubit, or quantum bit, is the quantum analogue of the classical bit in which classical information is encoded in 0s and 1s. So the qubit represents a quantum superposition, or simultaneous combination, of both a predetermined ‘0’ and a ‘1’ state. In paper by O’Malley et al., the quantum algorithms were run on superconducting qubits. These are a physical realisation of quantum bits based upon what are known as superconducting quantum interference devices (SQUIDs), and they are used here to find properties of the wavefunction of molecular Hydrogen.

The wavefunction of a quantum system is a mathematical construct describing the state; it provides probabilities for results of particular measurements made on the state. In quantum chemistry the electronic structure of a molecule is described by the movement of the electrons of a collection of fixed atomic nuclei. And thus a comprehensive description of the electronic structure encompasses the wavefunctions of all of these electrons, along with their respective energies. The idea that the motions of the electrons and nuclei may be considered separately is known as the Born-Oppenheimer approximation. It is a very useful assumption that simplifies electronic structure calculations appreciably.

One of the reasons that developing new approaches to tackling electronic structure calculations is of importance is that they are extremely computationally expensive. Indeed one of the original motivations for advancing the field of quantum computing was the desire to simulate quantum systems in nature through the use of quantum systems, and by so doing to circumvent the exponential computing power needed to do these simulations on classical hardware. A prominent driving factor in the interest in and development of quantum computing is the aim to create quantum hardware and software that will allow for efficient quantum simulations of quantum chem-

ical systems. Dr Abolfazl Bayat, a researcher at the Controlled Quantum Dynamics research group at UCL, states that “noise-resilient quantum computers would have transformative effects upon many fields, but especially in quantum chemistry where efficient quantum simulations would represent a significant leap forward for the field”. A problem of tantamount importance in quantum chemistry is that of finding the lowest energy eigenvalue of molecular electronic structures. These energy eigenvalues define a great deal of properties of interest in the molecule. This is of great importance in for example the development of pharmaceuticals where companies have an extremely laborious testing and trials process, if a significant part of the initial testing process could be done in silico - this would represent significant savings and would better ensure that the pharmaceutical under development behaved as required prior to starting trials.

4 Techniques in Paper

If I asked you how to make a cup of coffee, your response would go a little something like this; prepare a cup (clean of course), put a number of teaspoons of coffee (depends on how strong you like your coffee), boil the kettle, pour the hot water into the cup and lastly stir. You have now made your cup of instant coffee by following a set of instructions.

Now, imagine that I asked you to compute the energy surface of a given molecule; how would you carry out this task? You would execute an algorithm that produces a numerical value. In Scalar Quantum of Molecular Energies two techniques used to determine the energy surface for a hydrogen molecule are discussed as follows:

- The Variational Quantum Eigensolver (VQE)
- The Quantum Phase Estimation Algorithm (PEA)

which constitutes of the ‘original algorithm for quantum chemistry’.

4.1 The VQE Algorithm

Before we run our algorithm, it is imperative to understand that in quantum mechanics, the properties of a system are characterised by a state. Thus, we first need to prepare an initial state of the system (think of how you prepared the cup for the coffee following boiling water to be poured in). This is done by representing the state in a chosen vector v_0 . The vectors chosen are trial solutions (ansatz) since solutions are not chosen in reference to any specific value as such.

Once a variable is selected, we can find an estimate value of the energy corresponding to the chosen variable by measuring the average energy. The method utilised predicts the ground state, the lowest possible energy level of an atom. The values of the variable and estimate energy are then fed through a programme; this proposes settings for a new variable – let us call this variable v_1 . Comparing to our coffee example, it has been decided that either a new blend of coffee is necessary as the current coffee might be perhaps too strong!

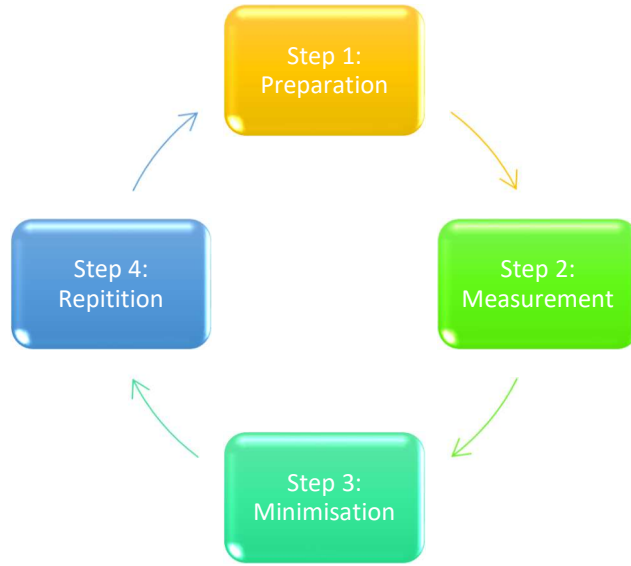


Figure 1: VQE flowchart

This process is repeated a number of times until the estimate energy approaches a specific value. The final result is an approximation of the smallest eigenenergy. Figure 1 illustrates the key outline of the VQE algorithm.

VQE

In 2014, the VQE algorithm was created by Alberto Peruzzo and Jarrod McClean. VQE comprises of classical and quantum features. This makes it possible to use both classical and quantum resources to determine solutions to problems that are difficult to solve using a classical computer. The flow chart indicates the key instructions of implementing the VQE algorithm. The steps are explained in further detail as follows:

1. Preparation: Prepare the initial state of the system in terms of the variable $\vec{\theta}$ by applying a quantum circuit. Implementing the unitary coupled cluster (UCC) method enables the algorithm to predict the ground state.
2. Measurement: Measure each local Hamiltonian, H_γ and its corresponding scalar g_γ to find the average value of the Hamiltonian [4, p.2].
3. Minimisation: Use a classical tool to find new solutions of theta in order to find the minimum eigenenergy of the Hamiltonian.
4. Repetition: By feeding the settings for $\vec{\theta}$ into the classical minimisation routine, the new settings for a new parameter of $\vec{\theta}$ i.e. $\vec{\theta}'$. This process is repeated for n iterations until the parameter converges towards to specific value; this will enable an ideal state of the system to be obtained. From this, one can deduce a particular value for E_0 , the smallest energy eigenvalue.

4.2 The Quantum Phase Estimation Algorithm (PEA)

Similarly, to the VQE algorithm, one must ensure that the system is prepared in an initial state, but with the exception that the state must have a sufficient overlap with the ground state. Once the state is prepared in our desired state, an approximation is applied to the phase of the operator. The operator $\hat{U} = e^{-iHt}$ enables the initial state $|\psi(0)\rangle$ to change over time to the state $e^{-iEt} |\psi(0)\rangle$. Consequently, the initial state is mapped onto a superposition

state of various qubits, which is called the ancilla qubits. After that, the state is acted on, in turn inducing a phase on the system. Since the way in which the system evolves is controlled, it is now entangled with the initialised state. Next, we measure the phase obtained corresponding to each value of energy. The system as a result collapses to a single state with an associated probability. We repeat this algorithm for a higher number of ancilla qubits [5, p.2] until the lowest eigenenergy is obtained, or more precisely the energy of the ground state.

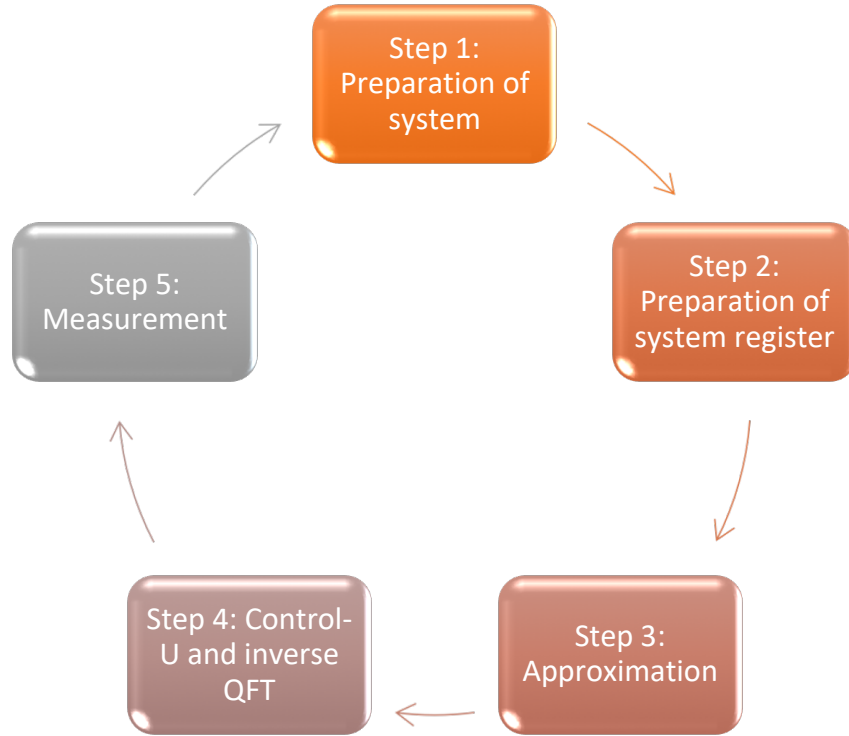


Figure 2: PEA flowchart

PEA

The PEA is a quantum subroutine of the original quantum algorithm for chemistry used to computer eigenenergies of a given molecular structure. As any state $|\psi(t)\rangle$ evolved by unitary can be represent by applying phase difference onto initial state $e^{-iEt} |\psi(0)\rangle$. Phase estimation algorithm (PEA) is used then to find this relative phase and convert it into energy. In order to preform PEA we need to prepare two parts of qubits. First n qubits of superposition state $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$, second, our initial state. Since we can evolve states by unity operator. By inputting both parts of qubits onto a multiple controlled-U gate, the eigenvalue of each unitary \hat{U} will transform to each one of qubits in first part.

Now let us recap Quantum Fourier Transformation, one transforms the tensor product of multiple states onto phase of some superposition states:

$$|j_1 j_2 \cdots j_n\rangle \rightarrow \frac{\overbrace{(|0\rangle + e^{2\pi i 0 \cdot j_n} |1\rangle) (|0\rangle + e^{2\pi i 0 \cdot j_{n-1} j_n} |1\rangle) \cdots (|0\rangle + e^{2\pi i 0 \cdot j_1 j_2 \cdots j_{n-1} j_n} |1\rangle)}^{\text{our prepared superposition qubits}}}{2^{\frac{n}{2}}}.$$

As we can see, the result of QFT is just the first part of qubits we prepared. Therefore we would apply the reverse QFT onto those qubits, and outputs a single state contains all information about phase we want. The algorithm then deduces the relative phase and converts it into energy.

4.3 Experimental Implementation

The most widely accepted prerequisites to build a viable physical quantum computing technology were proposed by the American physicist David DiVincenzo in 2000, with a few additional conditions added since. The original five DiVincenzo Criteria are:

1. Scalable physical system of well-characterised qubits.
2. Ability to initialize the state of the qubits to a simple fiducial state.

3. Long decoherence times, much longer than the “gate-operation” time.
4. Universal set of quantum gates.
5. Qubit-specific measurement capability.

There are a number of different approaches to building physical quantum computing hardware being pursued by various research groups and companies, each with their own advantages and disadvantages. Some of the types of experimentally implemented qubits include trapped ions, nitrogen-vacancy centres, quantum silicon photonics and superconducting, to name but a few. The qubits used to implement both the phase estimation algorithm and the variational quantum eigensolver were Xmon transmon qubits, a type of superconducting charge qubit built around a superconducting quantum interference device, or SQUID. Variations of the superconducting qubit are being developed by companies such as D-wave, IBM and Rigetti in the current race for quantum supremacy.

Experimental Implementation of Quantum Hardware

The physical quantum hardware used to implement the VQE and PEA algorithms are Xmon qubits. The Xmon qubit is a variation of the transmon qubit, a class superconducting qubit which uses superconducting quantum interference devices, also known as SQUIDs. It is a type of charge qubit, which is to say it is a qubit where its '0' and '1' basis states are charge states, and the superposition of these charge states is tuned using microwave resonators. The Xmon qubit has a number of favourable features, which include easy fabrication, fast qubit control and long qubit coherence times.

Using superconducting qubits is an appealing option for quantum hardware because it provides the scalability which is lacking for some other types of qubit. This is on account of the fact that for superconductivity the conduction electrons condense to a macroscopic quantum state which facilitates the creation of large integrated quantum circuits.

The Xmon qubits are placed inside a dilution refrigerator which is at a temperature of 20mK. The inter-qubit coupling, and qubit measurement and control, are all done using microwave resonators. Single (or local) quantum gates are achieved using pulses of microwave radiation. The entanglement operation used is the controlled-Z or CZ gate, this is achieved by fixing the frequency of one qubit while adiabatically tuning the other qubit from the $|11\rangle$ state to near to the $|02\rangle$ state, which gives a relative phase shift.

5 Main Achievement of paper

As it is known, building a quantum computer comes with many challenges, one being the aspect of scalability. One of the advantages of using PEA to compute electronic structures of a molecule is better asymptotic scaling which would prove useful for larger molecules than Hydrogen. However, this

is problematic as one would need to utilise more steps in the Trotterisation approximation which would in turn incur higher exponential costs. Hence, it was determined that a single Trotter step is not enough to accurately predict chemical rates for a Hydrogen molecule. In addition, for a single trotter step, each simulation using PEA was ran using different orderings of local Hamiltonians in order to find the optimal Trotter sequence for each bond length. For larger molecules, this is deemed intractable which becomes extremely difficult for the preprocessing requirements for a classical computer.

On the contrary, VQE was proved to be more effective due to its robustness to error. This is due to its success in predicting the chemical dissociation rate below the chemical accuracy threshold. Due to its short measurement sequences, it is more viable to use VQE for quantum simulations. Consequently, the quantum coherence of the system would be preserved which would limit the quantum error correction.

Although a quantum simulation such as the VQE is almost foolproof it may still not be adequate to calculate exact numerical solutions that are characteristic of various types of molecules and their interactions. It's hard to calculate energies to make such landscapes - Professor of Physics Dan Browne at University College London proposed that although VQE has a much simpler quantum circuit it still uses a classical search as part of the process to find these molecular energies. "VQE will only work If you have prior knowledge - this helps to refine the search. In the search, you need to look in the right place." He also commented "one could try combining both methods to make a better algorithm". Could combining PEA and VQE conjure up a huge amount of benefits so much that it reduces flaws such as noise and error intolerance?

Quantum computing shows promise to eliminate such errors whilst using a larger number of qubits. However, these factors work against each other. If such a machine can be built, there would be more states and thus information

to manipulate whilst withstanding error. This could revolutionise applications such as pharmaceuticals where cures and treatments for complex or incurable diseases such as Cancer, Prion disease and so forth could be engineered. If (or when should I say) this is possible, we would have a machine taking on the roles of a chemist, problem solver and designer simultaneously and combined into one entity!

6 Conclusion and Outlook

As this is the first scalable simulation of molecular energies on any type of quantum hardware it represents an important step in the history of quantum computing applications. The results indicate that for near-term quantum devices without effective error correction the adaptive approach represented by the variational quantum eigensolver may have better error resilience than that of standard gate model approach represented by the phase estimation algorithm. The expectation is that this work will pave the way for the development of further quantum techniques for calculations in quantum chemistry. And the final aim is that eventually these variational quantum chemistry techniques will allow for numerically exact simulations of chemical reaction rates, which are of great industrial commercial value. The VQE requires only short state preparation and measurement procedures, and so it is without the normal substantial overhead required for quantum error correction. This improves the efficiency and robustness to error displayed by the experimental implementation of the variational quantum eigensolver technique indicates that this technique might succeed where classical techniques fail in solving traditionally intractable problems.

Mikolaj Uryszek, a researcher in the Strongly Correlated Electron Systems group at UCL, commented that “variational techniques in quantum chemistry are becoming increasingly prevalent as a useful benchmarking tool to compare these early stage quantum devices, and this paper by O’Malley et

al. represents one of the most accurate quantum chemistry simulations using quantum hardware to date, and is a promising validation of the development of superconducting qubits for scalable quantum hardware”. And it certainly heralds an interesting future for the use both of superconducting qubits and variational quantum algorithms for tackling classically intractable problems in quantum chemistry and beyond.

Late last year the US passed the new National Quantum Initiative Act pledging around \$1.2 billion in funding for quantum information science [3]. At a similar time the EU commission launched the €1 billion Quantum Technologies Flagship which will fund over 5000 of the top European researchers in quantum technologies over the next decade [2]. In the UK, the EPSRC-backed Quantum Technology Hubs represent part of a £270 million investment to create national networks of quantum expertise [1]. With this extraordinary push of late across Europe and also in the US and China, aiming to fast-track quantum technologies out of university research groups and into industrial applications, the importance of this work in quantum chemistry cannot be overstated. As aside from the much touted almost pop-science status of quantum encryption and communication, the myriad opportunities afforded by more efficient and scalable quantum chemistry simulations looms large in garnering serious investor interest. The ability to run quantum simulations of the behaviour of atoms and molecules is hoped to offer new avenues for increasing our understanding of chemistry and enable the development of new medicines and materials *in silico*, thereby reducing the need for expensive trial-and-error approaches to research and development.

7 Afterword

This article is inspired by Scalable quantum simulation of molecular energies [4]. Shuhao Yang wrote the Introduction and History sections and the PEA section and box. James Mills wrote the Scientific Background and Conclusion

and Outlook sections and the Experimental Implementation section and box. Shanice St John wrote the Techniques in Paper section introduction and the Main Achievement of Paper section, and the VQE section and box. However we all edited and redrafted together and interviewed the academics whose opinions we quoted in the article. We would like to thank Dr Abolfazl Bayat, Prof. Dan Browne and Mikolaj Uryszek for kindly talking to us and allowing us to quote them here.

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