Quantum computing using continuous-time evolution[*]

Viv Kendon[†]

Durham University, Durham DH1 3LE, UK

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In the quest for more computing power, the dominant digital silicon architectures are reaching the limit of physically possible processor speeds. The heat conduction of silicon limits how fast waste heat can be extracted, in turn limiting the processor speeds. Moreoever, energy consumption by computers is now a significant fraction of humanity's energy use, and current silicon devices are orders of magnitude away from optimal in this respect. We can't afford to apply more and more standard computers to solve the biggest problems, we need more energy-efficient computational materials, and more efficient ways to compute beyond digital.

Quantum computing promises more efficient computation, at least for some important types of problems, such as simulation of quantum systems, non-convex optimisation, and (famously) factoring large semi-primes. However, the first useful quantum computers will be limited in what they can do. Applying them to bottlenecks that are hard for classical computers is key to extracting the best performance out of combined classical and quantum hardware. Using co-processors for specialised tasks is well-established, graphics cards have been standard for decades and dedicated chips for ethernet or wireless connections are common. Field programmable gate arrays (FPGAs) and application specific integrated circuits (ASICs) are now available in high performance computing clusters to speed up bottleneck subroutines. Adding a quantum co-processor is a natural extension of this trend.

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[†] viv.kendon@durham.ac.uk

The dominance of general purpose digital silicon devices has led to a lack of awareness of the breadth of diverse ways to encode and process information. Brains, bacteria ([Horsman et al.(2017)]), and analog computers all compute very differently from digical silicon. Quantum computing also has several different models of computation under active development. The gate or circuit model is most closely analogous to digital classical computing. A variant in which the computation is driven by measurements on a prepared entangled resource state provides extra efficiencies, for example, to speed up Fourier transforms. A fully analog version of quantum computing is relevant for some quantum simulation and communications tasks.

Using a digital encoding (qubits) combined with continuous-time processing is a natural way to compute with quantum systems, that does not have a classical equivalent. It encompasses quantum computing with continuous-time quantum walks, adiabatic quantum computing, quantum annealing, and a range of special purpose quantum simulators. The initial quantum state is evolved to the final quantum state using a continuous-time process. The Hamiltonian used evolve the quantum state encodes the problem, such that the ground state of the Hamiltonian encodes the solution. Efficient methods are known for encoding classical problems into Ising model Hamiltonians. The key question is thus how to apply the Hamiltonian to find the ground state as efficiently as possible. Which strategy is best depends on the hardware, especially in a practical setting where resources such as quantum coherence are severely limited. The shorter run times of quantum walks and quantum annealing may be favoured over slower adiabatic strategies, and hybrid algorithms exploiting the strengths of each strategy allow the best performance to be extracted from real hardware ([Morley et al.(2019)]).

Continuous-time quantum computing is especially promising for early quantum computing hardware. The devices built by D-Wave Systems Inc. have the largest number of qubits (around 2,000) currently available, although heavily influenced by environmental effects, and compute using a continuous-time evolution to solve optimisation problems. Specialist hardware for quantum simulation also usually evolves the quantum state in continuous-time, using an engineered Hamiltonian to match the one under study. Such hardware can potentially be used to solve other types of problems that can be naturally encoded into their Hamiltonians.

Digital quantum computers require error correction to be useful at larger sizes and the theory for this has been well-developed, although the number of extra qubits required is large. For continuous-time quantum computing there is no well-developed theory of how error correction could be applied in this setting. Techniques from quantum control theory and NMR control techniques can help to mitigate errors, and smart methods for encoding problems also make the computations more robust against errors. Ultimately, there are limits to how large such quantum computers can be, because larger numbers of qubits require more precisely specified Hamiltonian parameters. Since quantum simulation starts to become useful at around 50 qubits, there is plenty of room for useful and interesting computation on somewhat noisy, imperfect qubits, before these limits become significant. Moreover, digital quantum computers are not likely to be so useful until they do have sufficient error correction. Continuous-time quantum computers can thus bridge the gap until digital quantum computing is ready for large-scale deployment.

The theory of how to combine different types of computational devices has not kept pace with practice, and it is something of an experimental science to obtain efficient computing from such combinations. Some initial steps in how to do this at the algorithmic level have been presented by [Chancellor (2017a), Chancellor (2017b)]. This is the area in which work most needs to be done, in collaboration with potential user groups who know the algorithmic bottenecks they face that quantum computers can potentially bypass ([Harris & Kendon (2010)]). This will enable users to take advantage of quantum co-processors as soon as they become available alongside conventional HPC facilities. Test bed size quantum computers are becoming available to end users now, ready for early adopters to develop quantum enhancements to their algorithms.

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