We briefly review what a quantum computer is, what it promises to do for us and why it is so hard to build one. Among the first applications anticipated to bear fruit is the quantum simulation of quantum systems. While most quantum computation is an extension of classical digital computation, quantum simulation differs fundamentally in how the data are encoded in the quantum computer. To perform a quantum simulation, the Hilbert space of the system to be simulated is mapped directly onto the Hilbert space of the (logical) qubits in the quantum computer. This type of direct correspondence is how data are encoded in a classical analogue computer. There is no binary encoding, and increasing precision becomes exponentially costly: an extra bit of precision doubles the size of the computer. This has important consequences for both the precision and error-correction requirements of quantum simulation, and significant open questions remain about its practicality. It also means that the quantum version of analogue computers, continuous-variable quantum computers, becomes an equally efficient architecture for quantum simulation. Lessons from past use of classical analogue computers can help us to build better quantum simulators in future.

Keywords: quantum information; quantum computation; quantum simulation

1. Introduction

It is a quarter of a century since the seminal work of Feynman (1982) and Deutsch (1985) introduced the concept of quantum computation, and 15 years since Shor (1997) produced an efficient quantum algorithm for factoring large numbers, thereby raising the game for cryptographic schemes by suggesting that a quantum computer could break them more easily. Yet, working quantum computers are still just toys in a test tube performing calculations a child can do in their head. This is not for want of trying. Spurred on by the seminal work of Shor (1995), Laflamme et al. (1996) and Steane (1996), who showed how quantum error correction can

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be used to protect quantum systems from decoherence for long enough to run a
computation, the growth in research has been phenomenal on both theoretical and
experimental aspects of the challenge to construct a quantum computer. Steady
progress has been made over the intervening years, and there are a plethora of
promising architectures on the drawing board and the laboratory bench. There
is currently no clear front runner in the pack. We are at a stage of development
equivalent to that of classical computers before the advent of silicon chips (a mere
50 years ago). We know a lot about what a quantum computer should be able to
do, and what components it needs, but we have not identified the best materials
to build it with, nor what it will be most useful for calculating.

2. Quantum computing

Feynman and Deutsch both (independently) perceived that a superposition of
multiple quantum trajectories looks like a classical parallel computer, which
calculates the result of many different input values in the time it takes for one
processor to do one input value. Except that the quantum system does not need
a stack of CPUs, the parallel processing comes ‘for free’ with quantum dynamics,
potentially providing a vast economy of scale over classical computation. Of
course, there is no ‘free lunch’. Despite doing all the calculations in superposition,
we can only access one of the results when we measure the final state of the
quantum computer. Figure 1 illustrates schematically how a simple gate-model
quantum computer works.

Programming for a quantum computer is thus trickier than classical
programming: you have to include a step to select the answer you want (at least
with high probability) out of all the possible results. Quantum programming
techniques can be grouped into a few distinct types. Promise problems, like
Deutsch & Jozsa (1992), hidden subgroup problems, like Shor (1997) for factoring,
search algorithms like Grover (1996), and quantum versions of random walks
Some techniques are best understood as a different architecture, rather than a
different programming method. Minimization problems, such as finding ground-
state energies, or satisfiability problems (kSAT) are best tackled using adiabatic
quantum computation (Farhi et al. 2000). Adiabatic quantum computation has
been proved to be equivalent to the standard gate model of quantum computing
(Aharonov et al. 2007), meaning that we will be able to run adiabatic quantum
algorithms on any quantum computer.

Many of these potential applications will require very large quantum computers
before they gain an advantage over classical computers. For example, the best
classical factoring to date (Klejnjueng et al. 2010) took 2 years to factor a 232 digit
number (768 bits) from the RSA challenge list. Named after the inventors, Rivest,
Shamir and Adleman, RSA is a public key cryptography system in widespread
use. For an n bit input number, a basic implementation of Shor’s quantum-
factoring algorithm needs 2n qubits in the register that does the quantum Fourier
transform, plus 5n qubits for modular exponentiation, a total of 7n logical qubits.
A 768 bit number therefore needs 5376 logical qubits. For a quantum computer of
this size, error correction will be essential. How much this increases the number
of physical qubits depends on the error rates. The closer to the threshold rates

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Review. Quantum analogue computing

Figure 1. Digital quantum computation (gate model). Hadamard gates (H), controlled-not gates (CNOT) and measurements (M) are shown acting on a register of five qubits (black circles).

of $10^{-3}$ to $10^{-4}$, the more error correction is necessary (Devitt et al. 2009). These threshold error rates are smaller than any experiment has yet achieved. For low error rates, maybe 20–200 physical qubits per logical qubit are sufficient, while for high error rates (close to the threshold), it blows up quickly to around $10^5$ per logical qubit. This suggests that we may need teraqubit quantum computers to break factoring. While the scaling favours quantum, the crossover point is high.

The picture is rather more promising for using a quantum computer to simulate a quantum system, Feynman’s original inspiration for quantum computation. For example, a system consisting of $N$ 2-state quantum particles has $2^N$ possible states, and in general, it could be in superposition of all of them. Classical simulation of such a system requires one complex number per state, which amounts to $2^{N+1} \times$ size-of-double. With 1 gigabyte of memory, a system of $N = 26$ of the 2-state quantum particles can be accommodated. The record set by De Raedt et al. (2007) is $N = 36$ in 1 terabyte of memory. Each additional particle doubles the amount of memory required. Simulating more than 40 or so qubits in a general superposition state is beyond current classical capabilities. If the system is restricted to only part of its full Hilbert space, not all superpositions are needed, and with appropriately designed methods to take this into account, larger classical simulations are possible (Verstraete et al. 2004). This suggests that quantum computers with upwards of 40 logical qubits could perhaps do something useful for us that we cannot accomplish with classical simulation, in stark contrast to the teraqubits required for factoring.

While a classical simulation allows the full quantum state to be tracked throughout, data extraction from quantum simulations is not nearly so easy. Each run provides only a single snapshot of the outcome of a measurement on the superposition state of the system. But, methods have been designed for extracting key parameters, such as energy gaps (Wu et al. 2002), or correlation functions (Somma et al. 2002) from quantum simulations. Open problems in the theory of nanoscale superconducting materials are one example where quantum simulation could make an impact on the development of the field.

Quantum simulation has been demonstrated (Somaroo et al. 1999) for small systems using nuclear magnetic resonance quantum computers. So what is stopping us from building a quantum computer with 40–100 qubits tomorrow? Quite simply, this is extremely demanding technology to design and build. It
requires single quantum particles to be localized and controlled for long enough to apply hundreds or thousands of precise manipulations to them, singly or in pairs, and then measured individually with high fidelity. And throughout the process, unwanted interactions from nearby material or light must be prevented, or minimized, and any remaining effects reversed using error-correction techniques. Current state of the art for a quantum simulator is around 10 qubits. Scaling up to 50 with a few hundred manipulations is believable with the steady rate of development the experimentalists have been delivering. And it is believable that at around 50 qubits, a quantum simulator could perform a short computation without needing significant amounts of error correction. Going beyond this without error correction is stretching credibility based on what we know today. However, error correction designed for digital quantum computers does not work well enough for a quantum simulator. We will elaborate on this point in §4, after discussing simulation in general, to set the problem in context.

3. Simulation

Computer simulations play an important role in most areas of science. Numerical methods kick in wherever analytical calculations become too complicated or intractable, which can happen even for simple systems, like three bodies moving under their mutual gravitational interactions. We use computer simulation to test our models of the real world, by calculating in detail what they predict, then comparing this with our experimental observations. We do not expect perfect agreement, both experiments and computations have limited precision, and we may know the model is only an approximation (to simplify the computation). If our calculations and observations agree as well as we anticipate, this is evidence our models are good, and hence we understand at some level how the system works. We may then use our computer simulations to predict things we have not yet observed, or provide more details of processes that are hard to observe by experiment.

That computation of any sort works in a useful way is not trivial. An accurate calculation of the trajectory of a space probe that takes five years to reach its destination is crucial: we cannot just launch many test probes and see where they end up in order to work out which trajectory we want. One key difference between a classical physical system and a computer simulation of it is that we represent it using binary numbers (0 and 1) in a register in the computer. This is like the difference between counting on your fingers and writing down the number eight. Eight has just one symbol in place of your eight fingers. Eight people have 64 fingers between them and that only took two symbols to write down. This makes for a huge saving in the amount of memory a computer needs compared with the size of the physical system, see figure 2. Binary numbers mean counting using base two, whereas we usually use base ten. The saving in memory is huge whichever base we use, but the inner workings of the computer are easier to arrange using binary.

A second important reason why computer simulations work depends on the complexity of the model compared with the complexity of the system being studied. Stars and planets are highly complex systems, but we do not need to model most of the details to predict, to very high precision, how the planet will
orbit the star. Gravitation is a supremely simple theory compared with systems it can correctly describe the behaviour of. This is part of the way our world appears to be, described as the ‘unreasonable effectiveness of mathematics’ by Wigner (1960). More discussion of simulating complex classical systems, and how to apply quantum computers to this task, can be found in Harris & Kendon (2010), here we are specifically interested in simulating quantum systems.

4. Efficiency and precision

For practical purposes, an efficient computation is one that gives answers in relatively short human time scales (seconds, minutes, hours or days) at a cost we can afford to pay. Computer scientists make quantitative comparisons between different algorithms by associating a cost with each step of the algorithm, and with the amount of memory required to hold the data. This abstracts the idea that physical computers have a limited size (memory) and maximum rate of elementary calculation steps per unit time. In most cases, ‘efficient’ means the algorithms use resources that scale as a simple polynomial (like \( N^2 \)) of the size \( N \) of the problem.

If we could efficiently simulate a quantum algorithm on a classical computer, we would immediately have a classical algorithm that is sufficiently good to render the quantum algorithm superfluous. To prove an algorithmic speed up for a quantum algorithm, we have to prove that no classical algorithm of any type can do as well: such proofs are, in general, very difficult. Shor (1997) only found the ‘best-known’ algorithm for factoring, there is no proof something classical and faster cannot be found in future.

Just as we cannot usually make a perfect measurement that determines exactly how long or heavy something is, we also generally have to represent numbers in a computer to a fixed precision. As the computation proceeds, the errors due to the fixed precision slowly grow. For very long computations, they can overwhelm the answer and render it useless. The accuracy we require for our answer thus places another demand on how much memory and time we need to perform our computation. Starting out with a higher precision to represent our numbers allows high precision for the answer. If we represent our numbers as floating point with an exponent, e.g. \( 0.1011101101 \times 2^4 \), then for an error of size \( \varepsilon \), the number of bits (binary digits) of precision is \( \log_2(1/\varepsilon) \). For the example just given, which has 10 bits of precision, \( \varepsilon = 2^{-10} \). Efficient algorithms require resources (time and memory) that scale as \( \log_2(1/\varepsilon) \). Algorithms running on digital computers,

<table>
<thead>
<tr>
<th>number</th>
<th>unary</th>
<th>binary</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td></td>
<td>0</td>
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<tr>
<td>1</td>
<td>●</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>●●</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>●●●</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>●●●●</td>
<td>100</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>( N )</td>
<td>( N \times \bullet )</td>
<td>( \log_2 N ) bits</td>
</tr>
</tbody>
</table>

Figure 2. Binary counting needs exponentially less memory than unary.
that store their numbers in this binary format, usually have this logarithmic scaling for precision. However, for computers that store information in a unary encoding, such as quantum simulators, the errors will scale as $1/\epsilon$, thus requiring exponentially more resources for the same increase in precision as their binary encoded counterparts.

As well as errors arising from the limited precision, the operation of the computer itself may be imperfect and introduce random errors. In our present-day classical computers, such errors are so unlikely to happen that we can forget about them. In contrast, error correction for digital quantum computation will be essential beyond about 100 qubits and 100 computational steps.

5. Quantum simulation of quantum systems

The main reason why classical simulations of quantum systems are not efficient is because the memory required scales exponentially in the system size, due to the exponential number of quantum superpositions. This can be solved by using the efficient storage achieved by quantum computers. Mapping the Hilbert space of the system directly onto the Hilbert space of the quantum computer gives us efficient memory use. We also require that a quantum simulator can run using an efficient number of time steps. Lloyd (1996) showed that the Hamiltonian evolution of the quantum system can be decomposed into a sequence of standard Hamiltonians by using the Trotter approximation. Each standard Hamiltonian is applied for a short time to build up the desired evolution. The number of steps required scales polynomially in the accuracy, so this part of the algorithm is also efficient.

However, any small errors or imperfections in the operation of the quantum simulator will affect the result in a linear rather than logarithmic way, because the system is mapped directly onto the quantum simulator, rather than being binary encoded into numbers in qubit registers. Consequently, we will need exponentially more resources to correct for these errors. This raises the prospect of crippling error-correction requirements for practical quantum simulators (Brown et al. 2006).

Quantum simulation has much in common with analogue computation in the way the data are encoded. It shares the problem that an extra bit of precision requires a doubling of the resources. However, this suggests two avenues for the development of quantum simulation that have not yet been well explored. Firstly, looking back at the era of analogue computation can teach us lessons on how to make quantum simulation practically useful, despite the unfavourable scaling of the resources. Secondly, we can consider quantum versions of analogue computation for quantum-simulation architectures. We discuss both these ideas in the next sections.

6. Analogue computing

Despite the exponential saving in memory gained through binary encoding, the earliest computers did not use it. From the invention of the astrolabe for plotting the heavens in around 200 BC, through the slide rule, and mechanical differential analyser (Thomson 1876), these computational devices represented the quantity
they were computing as the size of some part of the apparatus. If you wanted a more accurate answer, you had to build a larger device: for another bit of precision, it would need to be twice the size. Yet, for the problems that these machines were designed to solve, they were very effective in practice.

Shannon (1941) provided a theoretical model, the general purpose analogue computer (GPAC), which is a mathematical description of the differential analyser. The GPAC consists of a set of nonlinear boxes, connected by their inputs and outputs. Four basic operations are sufficient, shown in figure 3. There are a few rules for how the boxes can be connected. Each output of a box goes to at most one input; inputs cannot be interconnected, i.e. there is no ‘splitter’ to allow the same input to go to more than one box; similarly, outputs cannot be interconnected. It has been proved by Pour-El (1978) and Lipshitz & Rubel (1981) that the set of functions generated in this way is the set of differentially algebraic functions. In other words, we can solve any ordinary differential equation with this type of device, given appropriate boundary conditions as part of the input. This abstract notion of computation can be realized in many different physical systems, such as water in pipes or electronic circuits. Such systems were quite common in university science departments before digital computers became widespread.

There have been a number of suggestions for how to expand the model by adding more operations to the available set, e.g. Rubel (1993), Graca (2004) and Mills (2008). These are mathematical extensions, and it is not clear whether they can be physically constructed, raising the question of just exactly what we can, in practice, compute given the way the physical world works. Rubel (1981) observed that there are simple differential equations that are universal in the sense that they can approximate any other differential equation to arbitrary accuracy. In practice, these are probably not useful for computation, attempts to build a circuit that implements such a differential equation turn out to be completely unstable (J. W. Mills 2009, personal observation). While Rubel (1989) proved that a classical digital computer can efficiently simulate an analogue computer, the reverse question of whether an analogue computer can simulate a digital computer efficiently is open.

Analogue computers might still provide a useful function in our digital world: for certain calculations they are extremely fast. When a specific task is required repeatedly (e.g. video rendering in real time), a dedicated analogue ‘chip’ might outperform a digital circuit.

7. Continuous-variable quantum computing

There is a fully quantum version of analogue computing, usually known as continuous-variable quantum computing (CVQC), and first described by Lloyd & Braunstein (1999). The information is encoded in the eigenstates of a continuous-spectrum operator such as position $\hat{x}$ or momentum $\hat{p}$. Computations

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are carried out by manipulating the physical states. Position and momentum are a conjugate pair of operators, which are orthogonal in the sense that \([\hat{x}, \hat{p}] = i\) up to a real normalization constant. They act on the Hilbert space \(L_2(\mathbb{R})\), the space of square-integrable functions over \(\mathbb{R}\) (square-integrable is important as it corresponds to being normalizable). To perform a quantum computation, we create an initial state, evolve the state in a prescribed way by applying an appropriate Hamiltonian to the state, and then perform a measurement from which we can extract the results.

Universal computation can be done in CVQC using a small set of elementary operations. Any Hamiltonian can be written as a Hermitian polynomial in the position and momentum operators \(\hat{x}\) and \(\hat{p}\), and we can generate any Hermitian polynomial in \(\hat{x}\) and \(\hat{p}\) by using the following set of operators (Lloyd & Braunstein 1999):

- simple linear operations, \(\{\pm \hat{x}, \pm \hat{p}\}\), and quadratic, e.g. \(\hat{x}^2 + \hat{p}^2\),
- a nonlinear operation at least cubic, i.e. \(\hat{x}^3\) or \(\hat{p}^3\), the Kerr Hamiltonian, \(H_{\text{Kerr}} = (\hat{x}^2 + \hat{p}^2)^2\), may be easier experimentally, and
- an interaction to couple two modes together, e.g. the beam-splitter operation.

It is easy to see how this works when the continuous quantity is the position, \(x\) (say). After evolving the state with some Hamiltonian, measuring the new position gives us the answer (or one possible answer out of a superposition or distribution). But the Heisenberg uncertainty principle means that if we know the position exactly, the momentum is totally undetermined. This asymmetry in the uncertainty is known as squeezing, and using a single quadrature like this requires infinitely squeezed states, which are unphysical. Experimentally, we cannot even get a good approximation of an infinitely squeezed state, so for practical purposes, we need to choose a different way to encode our information, and the obvious choice is to use Gaussian states, which have the uncertainty spread between the two quadratures \(x\) and \(p\). The nonlinear operation in our CVQC will evolve the state into something that is no longer a Gaussian state: if it did not, the whole computation would be efficiently classically simulatable (Bartlett et al. 2002). This corresponds to having a superposition or distribution of different answers: when we make a measurement, we will interpret the outcome as a Gaussian state from which we can extract the result of our computation.

Implementing CVQC in a real system may require some modification to the set of elementary gates, to adapt it to what is experimentally practical, for an example, see Wagner et al. (in press). While continuous variables are a practical choice for many quantum-communication tasks (see Braunstein & van Loock (2005) for a review), very little has been developed for CVQC. In particular, it shares the unfavourable scaling of resources with precision that classical analogue and quantum simulation have, and standard error-correction results for digital quantum computation do not apply (Niset et al. 2009).

8. Continuous-variable quantum computing for quantum simulation

For quantum simulation, where the digital advantage of binary encoding is already lost, CVQC deserves a critical second look. Many quantum systems are naturally continuous: for these, a CVQC quantum simulation would be especially

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appropriate. Experimental systems suitable for CVQC can be developed from many of the architectures currently proposed for digital quantum computing: whenever qubits are coupled using some sort of field mode, this can be inverted by regarding the field mode as the continuous variable and the qubits as the control system. Wagner et al. (in press) describe how the micromaser can be used in this way, and the photonic module of Devitt et al. (2007) is also promising. Squeezing is one of the elementary operations we need in CVQC when encoding with Gaussian states, and we can use the degree of squeezing to estimate how large our system needs to be to beat classical simulation. Suzuki et al. (2006) have achieved 7dB of squeezing in optical experiments. For one mode, 7dB of squeezing corresponds to 2–3 bits of precision, i.e. around five distinguishable outcomes when the state is measured. With arbitrary perfect coupling, going beyond what we can simulate classically corresponds to more than 17 modes coupled together, since the combination takes us above 40 equivalent (qu)bits. Experimentally, nine modes have been combined in continuous variable error correction by Aoki et al. (2009), though this stays within Gaussian states and is thus still efficiently classically simulatable. This is a very rough estimate because evolving the system accurately in a classical simulation would, in practice, require higher precision to produce the required final precision for the output. On the other hand, we cannot achieve arbitrary coupled states with current technology. However, it does give a feel for the potential for CVQC quantum simulation.

9. The future of quantum simulation

The goal of building a quantum computer large enough to solve problems beyond the reach of the classical computational power available to us is coming closer. The first useful application for quantum computers is likely to be simulation of quantum systems. Small quantum simulations have already been demonstrated, and useful quantum simulations—that solve problems inaccessible to classical computation—require less than a hundred qubits and may be viable without error correction. While the theoretical underpinnings of digital computation are well developed, there are significant gaps in our understanding of analogue-computing theory, and these are, in turn, slowing the progress of CVQC and quantum simulation. Investment in developing the missing theory is as crucial for the future development of quantum technology as experimental progress in quantum coherence and quantum control.

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