### QUANTUM COMPUTING

# In the 'death zone'?

An event advertised as the first demonstration of a commercial quantum computer raises the question of how far one can go with an 'do not care' attitude towards imperfections, without losing the quantum advantage.

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On 13 February this year, in a widely publicised demonstration[1], the company D-Wave Systems presented an implementation of a quantum adiabatic-optimization algorithm on their version of a 16-bit quantum computer. Unlike the conventional approach to building quantum computers, D-Wave's philosophy sidesteps the issue of having to endow the system with a built-in tolerance against a certain degree of imperfections (an approach known as 'fault-tolerant computing'). In fact, they argue that noise might actually be a good thing, at least when using — as the D-Wave team does — heuristic algorithms such as adiabatic optimization. Allowing noise to enter the system, and stepping back to see how well the quantum algorithm performs despite all imperfections might indeed be a good idea in view of the enormous experimental challenges posed by maintaining coherence among more than a few interacting quantum bits. The approach, however, can only go so far. Quantum circuits with error rates above a certain threshold enter a regime where everything they do can be simulated on a classical computer. Theoretical studies have recently significantly moved this threshold, thereby making it more difficult for those who want to implement quantum algorithms without worrying too much about the coherence of their systems.

Precisely how much noise is too much noise remains an open question. A few months ago, Buhrman and colleagues[2] predicted that an error rate of 45% per gate operation already takes a computation into a 'death zone' where nothing non-classical can happen. Building too noisy a quantum computer can, therefore, quickly turn into a losing proposition, at least as long as quantum computers are more expensive than traditional computers. The way the transition into a 'bad regime' is proven goes back to earlier work by Virmani *et al.*[3] and uses the notion that very noisy quantum operations can be viewed as probabilistic mixtures of more simple quantum operations that we know how to simulate classically (see Fig. 1). Any circuit made up of such noisy gates can therefore be simulated by a probabilistic, classical computation and hence can have none of the quantum benefits that we might be hoping for.

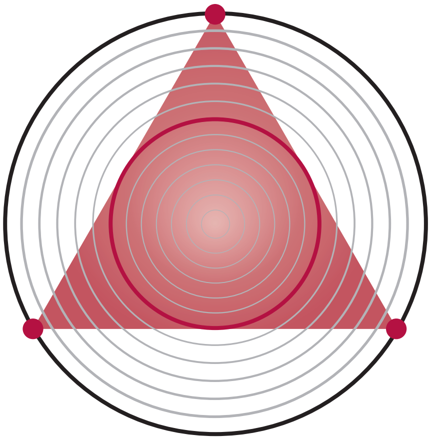

**Figure 1** Losing the quantum advantage. In this schematic picture, all operations that quantum mechanics permits can be represented by the circle (in black). A few of these operations — represented by red points — can be easily simulated classically, implying that all operations within the red triangle can be simulated classically as well, without anything 'quantum' happening. Any noisy system 'lives' within a concentric circle of smaller radius, and the noisier the system, the smaller the circle. If the circle of possible operations is smaller than the 'threshold' circle (in red), any computation the system can perform can equally well be achieved classically.

Constructing a reliable device that is capable of processing information in a quantum mechanical way poses a formidable challenge. The logical quantum bits have to be implemented in a way that makes them sensitive to quantum mechanical effects, while at the same time this behaviour should not be disturbed by the noise of its surroundings. No matter how well designed our future quantum computers will be, they have to be able to deal with the inevitable occurrence of errors — like every classical computer[4]. The theory of fault-tolerant computing looks at designs of quantum circuits that are able to withstand errors by storing the logical quantum bits in a redundant way, making it possible to detect and correct the errors before they affect the rest of the computation. The celebrated threshold theorem[5] in quantum computing tells us that if the error rate of our components is small enough, then the benefits of using quantum error correction outweighs the overhead that is needed to do so.

Fault-tolerant computing below such a noise threshold is like a self-supporting ecosystem: although components die and garbage is produced, the dynamics of the system take care of such disruptions and without the need for external intervention it can maintain its complex behaviour indefinitely. Finding such a threshold is important; if the circuit has an error rate per elementary gate operation of no more than some threshold value $\tau$, then it is possible to construct reliable quantum circuits of arbitrary size. This should be contrasted with the fact that for the same error rate, the naive approach will only have reliable computation for timescales proportional to $1/\tau$.

Why then don't we have large-scale quantum computers already? Unfortunately the best known thresholds values for tolerable error rates are still very demanding, between $10^{-3}$ and $10^{-5}$, depending on the specifics of the architecture. Even the current best experiments suffer from much higher error rates than that. To bridge the gap between theory and practice, researchers work from both sides: experimentalists try to reduce the noise levels of their systems while theorists try to design better fault-tolerant schemes that allow higher error rates.

In light of the experimental challenges that we are facing, it would be useful to know what the best possible thresholds could be. Maybe the current threshold values are overly pessimistic, and thus D-Wave might have a point when gambling on the quantum adiabatic algorithm to ensure that computations survive the error rates of their implementation. But the work of Buhrman *et al.*[2] shows that this kind of optimism has its limits: if the device is too noisy, any problem that it can solve can also be solved with the same efficiency using a standard laptop computer. To return to the analogy of fault-tolerant quantum computing as a self sustaining ecosystem: for error rates that are above a threshold of 45%, the landscape resembles more the 'death zone' on the top of a mountain where no quantum computation can survive for a significant amount of time and all that remains is classical computation.

At the moment it is impossible to say if D-Wave's quantum computer is intrinsically equivalent to a classical computer or not. So until more is known about their error rates, *caveat emptor* is the least one can say.

## References

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