News & views

Quantum information

Loops simplify a set-up to boost quantum advantage

Daniel Jost Brod

An optical device uses fibre loops to improve an experiment designed to show that quantum systems have the edge on classical computers. The innovative scheme offers impressive control and potential for scaling. **See p.75**

Gone are the days when advances in quantum computing were restricted to proof-of-principle devices – physicists can now control quantum systems well enough to make them outperform classical supercomputers for certain calculations. Fully fledged quantum computers are still a distant prospect, but Madsen *et al.*[1] have taken us a step closer to making such devices a reality. On page 75, they report the construction of Borealis, a quantum device that takes just 36 microseconds to perform a task that would take a classical supercomputer several thousand years to complete, even with state-of-the-art algorithms. The speed-up was made possible by the clever use of optical fibre loops to simplify previous record-holding quantum experiments.

Many applications have already been proposed for when large-scale quantum computers do become a reality. They could be used to factor large numbers, compromise certain cryptographic schemes, or simulate systems of interest in quantum chemistry, biology and possibly pharmaceutical research. Unfortunately, a quantum computer capable of such tasks would require millions of controllable, robust quantum bits (qubits), whereas current quantum processors have fewer than 100 qubits[2,3]. And because classical computers have a head start of at least half a century, both in algorithm design and device miniaturization, one might worry that quantum computers are still decades away from catching up with their classical counterparts.

Thankfully, quantum-computing researchers have a medium-term goal, known as quantum advantage, which shifts the focus from clear-cut practical applications to the more modest objective of finding a task – any task – that quantum devices can perform
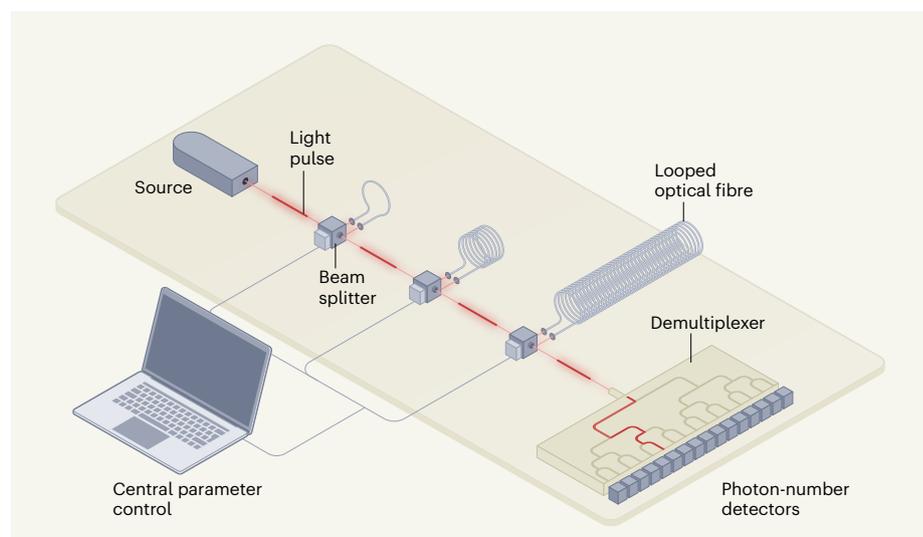
faster than can classical supercomputers. The goal is to showcase the raw computational power afforded by quantum mechanics, with, it is to be hoped, considerably fewer resources than are needed for factoring or quantum simulation.

One proposal for showing quantum advantage is Gaussian boson sampling[4,5], which involves preparing special states of light (known as squeezed states), directing

them through a network of beam splitters (semi-reflective mirrors) and counting how many photons arrive at each detector. The optical techniques needed for this experiment are well established, as is the theory that can be used to calculate how difficult the task would be for classical computers to perform. Such estimates suggest that an experiment performed with a few hundred photons would already pose a substantial challenge to the simulation capabilities of current supercomputers.

Madsen *et al.* have now taken up this challenge. They are not the first researchers to perform a large-scale Gaussian boson sampling experiment – previous efforts using 76 and 113 photons have already been reported[6,7] – but the team's approach improves on these achievements in crucial ways.

First, it assigns the photons to different bins depending on the time at which they arrive at the detector. A more common classification scheme labels the photons by their direction of travel, but Madsen and colleagues' encoding labels a photon's state according to whether it passes through a given position at some discrete multiple of a certain time interval. Using loops of optical fibre, it is possible to

Figure 1 | A quantum experiment that outperforms a classical supercomputer. Gaussian boson sampling is a scheme designed to demonstrate the advantages of quantum devices over classical computers. The experiment typically involves preparing special light pulses at a source, sending them through a network of beam splitters (semi-reflective mirrors) and counting how many photons arrive at a detector. Madsen *et al.*[1] improved this set-up by using loops of optical fibre to assign photons to bins describing discrete multiples of a certain time interval. In this way, they were able to use only three beam splitters, although the experiment would work with just one. The loops incorporate delays that make different time bins interfere at a specific position. A device called a demultiplexer 'spreads out' the photons to make them easier to detect. In this way, the authors were able to replace a complex network of beam splitters with a sequence of only three elements connected by fibre loops, enabling them to specify parameters centrally in real time, and making their device easy to configure. (Adapted from Fig. 1 of ref. 1.)

incorporate delays that allow photons in different time bins to interfere at a specific position (Fig. 1). This means that a large network of beam splitters can be replaced by a single beam splitter, which is coupled to fibre loops that must be long enough to accommodate all the required delays. In practice, Madsen and co-workers' set-up incorporated three beam splitters connected by fibre loops.

Second, Borealis can be readily reconfigured. Previous experiments typically relied on static networks, in which each component is fixed once fabricated[6,7]. This feature trades programmability of the device for ease of implementation and scaling. Although some programmable devices have been demonstrated[7,8], none has been as comprehensively configurable as Borealis, the optical elements of which can all be readily programmed. In other words, the reflectivity of a beam splitter can be tuned in real time. This is made possible by the binned encoding scheme: because the device uses a system of only three beam splitters, it is possible to change their parameters between the arrival of photons in one time interval and the next.

Finally, a major concern is how to certify that the output data are correct. In contrast to other tasks (such as factoring) for which it is easy to check an answer, the complexity of quantum-advantage demonstrations often seems to prevent verification that an operation is even approximately correct. To circumvent this, statistical tests can be used to rule out alternative answers, but they cannot fully determine an output. This introduces a problem known as spoofing, in which classical algorithms that do not faithfully reproduce a quantum output can mimic it well enough to pass these statistical tests.

Madsen et al. ran a comprehensive set of tests on the output of Borealis, and showed that it could not be spoofed, even by algorithms that were tailored to spoof previous experiments on Gaussian boson sampling. This provides some evidence that the experiment is robust to spoofing, but it might not be the end of the story — one such algorithm was developed after publication of the experiments it spoofed[6,7], and was tailored for the task[9]. Algorithms that better mimic the output of Borealis will no doubt also arise, which will in turn lead to more-sophisticated statistical tests to rule them out.

Quantum advantage is not a well-defined threshold, based on a single figure of merit. And as experiments develop, so, too, will techniques to simulate them — we can expect record-setting quantum devices and classical algorithms in the near future to take turns in challenging each other for the top spot. Madsen and colleagues' work is a leap forward for quantum physics in this race. It also solves technological challenges that might put us ahead in the longer race towards viable quantum computers, and that are likely to prove useful for other aspects of quantum information processing.

Daniel Jost Brod is at the Physics Institute, Federal Fluminense University, Niterói, Rio de Janeiro 24210-346, Brazil.
e-mail: danielejostbrod@id.uff.br

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Neuroscience

Nerve regrowth can be painful

Suna L. Cranfill & Wenqin Luo

Neuronal fibres have been tracked as they regrow into the skin following nerve injury in mice. The analysis reveals that mis-wiring of pain-sensing fibres generates hypersensitivity to touch in skin associated with the injury. **See p.137**

Pain provides an essential warning of impending tissue damage, protecting us from worse injuries. But when our nervous systems are damaged, this transient warning can turn into a persistent and debilitating pain[1]. The mechanisms that underlie this neuropathic pain are incompletely understood, leading to inadequate treatment options. Gangadharan et al.[2] report on page 137 their ten-month analysis of mice recovering from nerve damage.

> **"The authors' work adds to a growing appreciation of the complex link between pain and nerve regeneration."**

The authors describe a surprising link between neuropathic pain and reinnervation.

Research on nerve damage in rodents often involves the spared nerve injury (SNI) model. The sciatic nerve sends three branches down the hindlegs of rodents — in the SNI model, two of these branches are severed. This leads to loss of nerves in the regions of the skin supplied by the severed branches (the denervated side), but not of those in the skin innervated by the spared nerve[3]. Within a few days of the injury, the skin innervated by the spared nerve develops a condition called mechanical allodynia, in which normally innocuous stimuli, such as gentle touch, are perceived as painful. This hypersensitivity to touch can persist for months.

Most studies involving the SNI model have focused on this pain in the spared territory. By contrast, Gangadharan et al. focused on the denervated side, studying neural regrowth for up to 42 weeks after SNI in mice, by means of a non-invasive imaging technique. They used genetic engineering to label two types of sensory neuron — tactile fibres, which are sensitive to light touch, and nociceptors, which are sensitive to strong mechanical forces and other noxious stimuli. As a result, the fibres expressed fluorescent proteins, enabling their growth to be tracked under a microscope. The group also assessed the animals' behavioural responses to mechanical stimuli throughout the 42-week period.

Nociceptors, but not tactile fibres, began reinnervating the denervated territory around eight weeks after SNI. This correlated with a regained response to strong mechanical forces such as robust prodding. As nociceptor reinnervation progressed, however, the mice began to show hypersensitivity to gentle forces. Cutting the spared nerve eliminated these nociceptor fibres, indicating that they were sprouting from the spared nerve. Gangadharan et al. showed that nociceptors are responsible for mechanical allodynia in the reinnervated territory after SNI, but not for that in the spared territory. This is a previously undescribed type of SNI-induced mechanical allodynia, which the authors termed reinnervation-induced neuropathic pain.