between the two 'mirrors' several times before dissipating. The SET detector also sat on the surface of the slab inside the cavity. Every time the surface wave passed under the SET, the rapidly oscillating polarization charge accompanying the SAW modified the SET island potential. Although these oscillations were too fast to directly resolve (they lie outside the bandwidth of the radiofrequency SET), they do lead to a modification of the SET's response to an additional, external gate potential. It was this change in response that was directly measured and used to extract the displacement of the SAW pulse.

The experiment showed an impressive sensitivity, reporting a three-orders-of-magnitude improvement over previous work using either quantum dots[9] or a scanning probe[10] for SAW detection. Even more strikingly, Gustafsson *et al.* demonstrated that with sufficient averaging (10 million repetitions), they could detect a SAW coherent-state wavepacket whose average energy corresponded to 0.6 energy quanta. Using this, they inferred that with a further improvement of sensitivity by about 500, they would be able to detect a single-phonon wavepacket in a single run of the experiment (single-shot detection).

Although this sensitivity is impressive, it is still far from the state-of-the-art in quantum optomechanics[11], where optical or microwave cavities measure mechanical position with sensitivities at the level of a single energy quantum. However, these optomechanical systems typically involve much lower frequency modes, making it more difficult to reach the quantum regime. In contrast, higher-frequency suspended mechanical structures suffer from far higher levels of dissipation (that is, far lower quality factors), making them less suitable for studies of quantum phenomena. In contrast, SAW cavity modes can have both high frequencies (as demonstrated here) as well as high quality factors. This experiment thus provides a new route to quantum-limited detection of high-frequency ultralow-dissipation mechanical modes.

Perhaps even more exciting is the fact that this experiment opens the door to quantum phononics — the study and control of the quantum properties of propagating mechanical modes. Gustafsson *et al.* have demonstrated that sensitive displacement measurement is possible even in the absence of mode localization. This new line of research could have applications to quantum information processing, as well as to more fundamental issues. Already, the experiment of Gustafsson *et al.* raises several interesting questions pertaining to quantum measurement. How does one fully understand the backaction of such a measurement? What are the ultimate limits on this sort of quantum-displacement detection? Could this system be modified to approach an ideal non-demolition measurement, where properties of the propagating mode are measured without any backaction disturbance whatsoever? No doubt these and related questions will keep researchers in this emerging field busy for some time. ❐

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OPTICAL COMPUTING

Photonic neural networks

Optical computers will be more interesting if they take advantage of phenomena that are unique to optics. In this respect, telecommunications hardware might have something to offer.

Damien Woods and Thomas J. Naughton

In the centenary of his birth, we celebrate Alan Turing (www.nature.com/turing) for inventing the revolutionary concept of computational universality. Turing's falsifiable definition of what a general-purpose computer can do is still widely accepted today. Scientists and engineers have yet to build a physical computer whose entire computing repertoire cannot be simulated by Turing's gedanken computer from 1936.

Turing's computer used a string of binary symbols to represent numbers, a feature still present in digital electronic computing. In contrast, many early realizations of computers, both before and after Turing, were analog computers where individual numbers were encoded as physical quantities such as current. Analog computing continues to generate interest. Laurent Larger and colleagues, and Yvan Paquot and colleagues, writing in *Optics Express*[1] and *Scientific Reports*[2], respectively, approach analog computing by using light intensity to encode data. Their goal is the optical implementation of an artificial neural network — a model that is inspired by the working of the brain and has a long history in optical computing. The type of network they implement is called a reservoir computer (or echo-state machine or liquid-state machine) where each node has a time-varying real-valued state that is iteratively updated by computing a nonlinear function of its own state and the weighted states of its neighbours. Implementing an arbitrary network of interacting nonlinear optical components is challenging, so simplifications are introduced[1–3]. One simplification is to restrict the network to a cyclic form so that each node connects only to its immediate neighbours (Fig. 1a). Indeed, such cyclic networks can solve interesting computational tasks[4]. Another simplifying modification is to use a clever time-multiplexing technique[3] that enables just one nonlinear device to effect a cyclic network of N nodes, albeit with some slowdown. It is interesting that the dynamics of the analog optical device

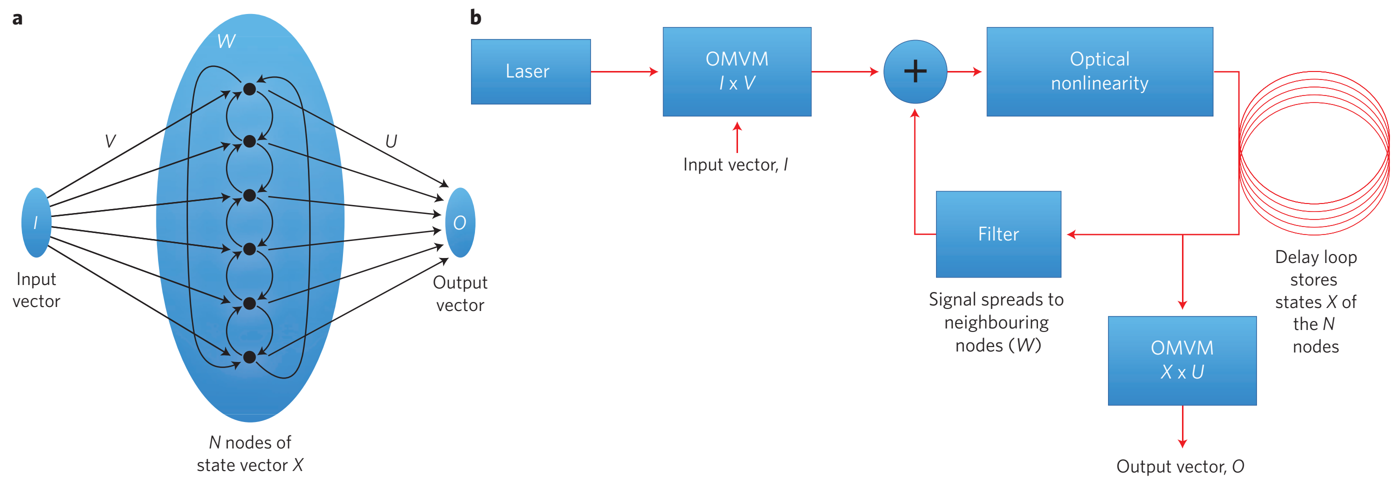

Figure 1 | Optical computing. **a**, An artificial neural network of the type[4] implemented by Larger *et al.*[1] and Paquot *et al.*[2] Each node computes a nonlinear function of the sum of its inputs. *V*, *W* and *U* are real-valued matrices that weight the contribution of inputs, states and outputs, respectively. **b**, Optoelectronic artificial neural-network implementation. The state vector *X* of the *N* network nodes is represented as *N* intensity values that travel around the optical fibre loop. At each discrete time instant, the input vector *I* is multiplied by the input weight matrix *V* using an optically implemented (constant time) matrix-vector multiplier (OMVM). The resulting vector is fed, entry by entry, into the optical fibre loop so that each entry can be summed with the state of one of the *N* nodes. An optical nonlinear device computes the nodes' nonlinear function. A low-pass filter implements the cyclic network (*W*) connectivity, with an optical amplifier if needed. The final output vector is produced by tapping the fibre and applying an OMVM . The high-level design extends that of Larger *et al.*[1] and Paquot *et al.*[2]; the addition of the two OMVMs improves the running time from $O(N^2)$ to $O(N)$, and uses features that are unique to optics (reconfigurable large fan-in).

enable it to achieve results comparable to the state of the art for hard problems such as speech recognition[1–3].

New optical computing advances should be discussed in the context of the recent debate in *Nature Photonics*[5–8], which included H. John Caulfield who sadly passed away this year. Larger and colleagues[1], and Paquot and colleagues[2] both cite this discussion. A core issue in the debate[5–8] is that special-purpose computationally efficient optical devices should be presented in terms of their cascadability, energy costs and applicability to general-purpose computation. A further argument[5–8] is that any claims for optics replacing electronics in computing should be couched in terms of continuous advances in existing technology and relevant economic factors.

The first point we would like to make is that comparisons with digital electronics should not completely overshadow other scientific motivations for exploring computers that harness natural processes. For example, we could understand a cell by inducing it to run a modified DNA program, we could understand the nervous system through the use of massively interconnected networks, or we could use computation to prove the impossibility of predicting a simple physical system even with known initial conditions. Certainly, Shor's quantum factoring algorithm[9] is remarkable in that its mere existence on paper is enough to tell us that, assuming quantum mechanics is valid, either a widely held view in cryptography (that factoring is computationally hard) or one in computer science (that a certain class of computers can efficiently simulate each other) must be incorrect.

Debate in the community has focused on the difficulties associated with successful realizations of optical logic gates or optical transistors[6–8]. The second point we would like to make is that circuit-like architectures are not the only way to implement optical computing. One interesting novelty in the work of Larger *et al.*[1] and Paquot *et al.*[2] is the use of hardware that is more traditionally associated with optical communications. One could consider their optical fibre-based buffer as a time-of-flight addressable memory, where a one-dimensional sequence of data points continuously traverses a fibre loop with low loss. Even though this is impractical for extremely large memory sizes[10], the approach begs the question: are there new and interesting ways to solve computational problems using well-understood optical communications hardware?

Our third point concerns how to use optics for computing. Whether for industrial impact or purely theoretical interest, we believe that the most successful optical computing paradigms will be those that use phenomena that are unique to optics. In this context, the schemes of Larger *et al.* and Paquot *et al.* act like a sequential computer (such as a Turing machine), so that the natural, and potentially powerful, parallelism of optics is not used. The existing design uses significant pre- and post-processing in software (including matrix and vector products that are even more complicated than those performed optically), as the authors acknowledge. The neural-network training is also a good candidate for parallelization. Perhaps it is not so difficult to address some of these issues while maintaining the simplicity and novelty of having only one nonlinear element. Figure 1b shows their design[1,2], but with additional parallel optoelectronic matrix-vector products for pre- and post-processing. This cross-fertilization between fibre optics and free-space optics may or may not be straightforward to implement, but we suggest it with the motivation of using phenomena that are unique to optics; in this case, the number of parallel input interconnections, referred to as the fan-in, is reconfigurable and large. Although large fan-in is not popular in transistor-based computers, it imparts computational efficiency[9] and might be a useful property in other models, such as optical matrix processors. Even though there are implementation difficulties to overcome, such as optical power loss and unequal optical path lengths, the computational universality[9] of matrix processors makes them appealing: they are as computationally powerful as the transistor-based model.

Probably no computing paradigm will be competitive with digital electronics in the near future, but this should not be the only goal when considering alternative methods of computing. Sometimes we simply find ourselves asking the question: how does nature compute? ❐

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CELL MECHANICS

Forced to branch out

Migrating cells are capable of actively opposing external forces. A study of the polymers that mediate cell motility indicates that they effect this response by branching where bent under force.

Anders E. Carlsson

The cytoskeleton is a crosslinked network of biopolymers that gives biological cells mechanical integrity and generates force for cell migration. One remarkable feature of the cytoskeleton is its active opposition to externally applied forces. Cells placed under tension respond actively by generating rubber-band-like contractile structures. Migrating cells encountering barriers crank up their force-generation machinery to penetrate the barriers — in some cases even migrating in opposition to an applied force[1].

Such phenomena are usually attributed to the action of complex biochemical signalling networks controlling the cytoskeleton. However, the observation of an active response in force–displacement curves for very simple biochemical mimics of the cytoskeleton[2] suggests that more direct mechanisms can cause such oppositional behaviour. A recent paper in *Proceedings of the National Academy of Sciences* by Viviana Risca and colleagues[3] identifies such a mechanism of active cytoskeletal response in cells: forces exerted on the cytoskeleton bend its polymers, and this bending in turn causes the cytoskeleton to grow in opposition to the force.

Risca *et al.*[3] used high-resolution light microscopy to study key steps in the polymerization of the protein actin. Actin, one of the two main constituent proteins of the cytoskeleton, polymerizes into filaments with varying lengths. Near the cell membrane, actin often forms a network of filaments a few tenths of a micrometre long. This network results from a branching growth mechanism in which 'daughter' filaments grow from the sides of 'mother' filaments, with a well-defined branching angle of about 70° (Fig. 1a). This is accomplished using the Arp2/3 complex — a group of seven protein subunits that binds to the side of an existing mother filament and, in a Lego-like fashion, forms a scaffold for a new daughter branch. Branches formed near the cell membrane impinge on the membrane and thus generate the forces required for cell migration or protrusion.

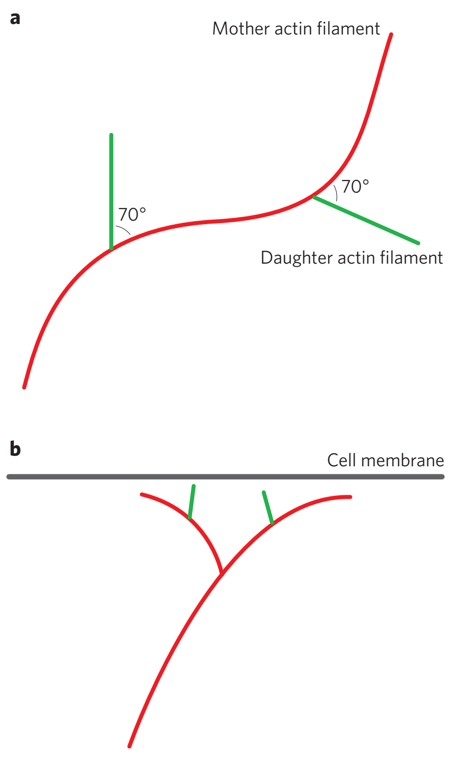

Figure 1 | Branching on curved filaments. **a**, A mother actin filament (red) with frozen-in curvature from the substrate generates new (daughter) branches (green) more frequently on the convex sides of the mother filament. **b**, Force exerted by the cell membrane causes actin filaments to curve away from the membrane, enhancing the growth of new branches towards the membrane.

The group studied a solution containing fluorescently labelled actin monomers, Arp2/3 complexes and a catalyst, in which actin filaments grew and branched[3]. The filament geometry and branching were evaluated by chemically attaching the filaments to a substrate, and imaging them using fluorescence microscopy.

Because each filament was attached to the substrate at many points, curvature was frozen-in. Measurement of the branch positions and orientations, and the curvature of the filaments, showed that branches formed more frequently on the filament sides with convex curvature, which are stretched when the filament is bent (Fig. 1a). Filament segments with a convex curvature of 1.5 μm^{-1} had approximately twice as many branches as filaments with a concave curvature of equal magnitude.

By calculating the fluctuations in small-scale curvature at average curvatures commensurate with those measured, Risca *et al.*[3] argue that the asymmetry results from a shift in the distribution of local curvature fluctuations rather than changes in the average value. This shift leads to large fractional changes in the wings of the distribution, suggesting a fluctuation–gating model, in which branches occur only when the local convex curvature exceeds a threshold value. Fitting