phenomenon that really drives the science. Alternatively, they might have restricted the analysis to one country, thus failing to exploit the full power of the data at hand. But the sophisticated geospatial tools used in the current work employ clever numerical approximations to sidestep the computational bottlenecks posed by analysing so many correlated observations. These methods are applicable to much more than just the public-health domains described here, and should provide scientific insights in many disciplines. Of course, it is important that these powerful statistical tools are not applied blindly. In both papers, the authors are careful to weight data appropriately and to validate their predictions at each step.

There is much excitement these days about the way in which enormous data sets are helping us to address many hard scientific challenges. In reality, data sets are useful only when combined with a deep understanding of the relevant science, economics or sociology, such as the impact of culture in a particular region, or details about how diseases spread. A solid understanding of how data are collected is also crucial. Rigorous scientific advances emerge when interdisciplinary teams work closely together — the current papers, which involve researchers trained in epidemiology, statistics, demography and public health, are prime examples of this.

The ultimate goal of a spatial analysis is to design interventions for maximum impact. If we understand a spatio-temporal process, we can optimize the allocation of resources in space and time. For example, consider the spread of malaria, and the effect of interventions such as bed-net distribution. A 2016 analysis[4] considered several malaria interventions, and determined the most cost-effective intervention for each 5-km^2 pixel in Africa on the basis of spatial variation in climate, mosquito populations and the current state of the disease. The results from Osgood-Zimmerman *et al.* and Graetz *et al.* should prove useful in an analogous study of optimal interventions for nutrition and education. We believe that we are entering an era in which this type of analysis can be applied broadly to improve the lives of people around the world. ■

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QUANTUM COMPUTING

Qubits break the sound barrier

Quantum logic gates based on trapped ions perform more accurately than solid-state devices, but have been slower. Experiments show how trapped-ion gates can be sped up, as is needed to realize a quantum computer. SEE LETTER P.75

TOBIAS SCHAETZ

One of the goals most eagerly pursued by physicists is the development of a universal quantum computer — a machine capable of running a superposition of many correlated tasks, and one that would offer much better performance for dedicated jobs than do conventional computers. One of the most promising approaches is to use systems of trapped ions. Such systems provide the best fidelities[1,2] for all quantum logic operations (that is, they most reliably produce the correct outputs for a given input), including operations performed by the logic gates needed to process quantum bits (qubits).

Two-qubit gates are needed to implement quantum computers that can run any algorithm. In trapped-ion systems, two-qubit gates carry data between ions using phonons (quantum units of vibration) associated with the collective oscillation of the ions[3]. However, the operating speed of the gates has been limited by the oscillation frequency, which defines the speed of sound in the ensemble of ions and therefore sets the speed limit for communication. Several strategies have been proposed to overcome this limitation[4–8]. On page 75, Schäfer *et al.*[9] report the experimental realization of one such strategy, building on previously reported work in this area[7,10]. The researchers find that the speed of their two-qubit gates is more than ten times that of previously reported trapped-ion gates.

The basic principle of two-qubit gates is reminiscent of classical logic gates. Let's consider a classical controlled NOT (CNOT) gate, which turns four possible input states (00, 01, 10 or 11) into four output states (00, 01, 11 and 10, respectively). In other words, the second input bit (the target bit) is flipped between the 0 and 1 states only if the first bit (the control bit) is 1.

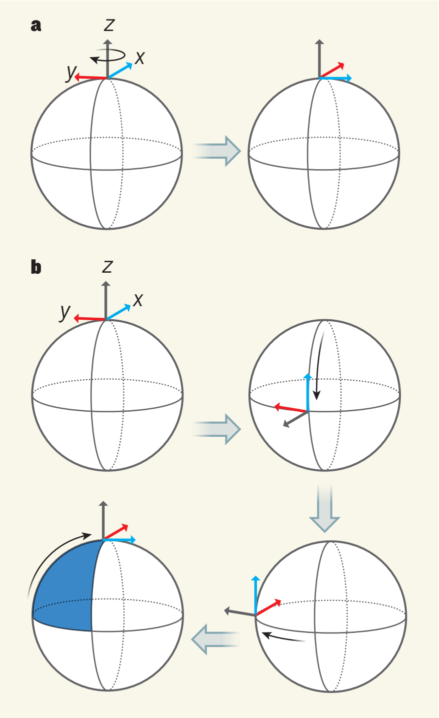

Figure 1 | Dynamical and geometric phase generation. a, When a physical state that can be described using *x*, *y* and *z* axes is placed at the north pole of a sphere, a property known as dynamical phase is generated by rotating the system around its *z* axis. The phase change equates to the change in the orientation of the *x* and *y* axes relative to their original ones. **b,** If the physical state moves down the surface of the sphere to the equator, then along the equator and back up to the north pole, the net result is rotation of the *x* axis, as in **a**. This phase change is proportional to the area enclosed by the pathway taken (blue region), and is called a geometric phase change. Schäfer *et al.*[9] report a method for generating geometric phase changes of trapped ions, and use it to implement quantum logic gates that operate much faster than similar, previously reported trapped-ion gates.

The quantum version of the CNOT gate allows much more than these four states to be processed. For example, the control qubit can enter the gate in a superposition state, 0 + 1. If the target qubit is 0, then running the same logic operation as for the classical CNOT flips and unflips the target at the same time. The two qubits thus end up in the final state of 00 + 11, which is a maximally entangled state: the measurement of one qubit yields a completely random output, but instantaneously fixes the state of the second qubit to be identical to that of the first, regardless of the distance between the qubits. This correlation could form the backbone of a quantum computer — it allows many operations to be run in parallel, so that a superposition of all possible inputs yields all possible results at once.

The two-qubit gate implemented by the authors can be seen as a CNOT gate, in which qubit information is encoded in quantum 'phases'. To picture what this means, imagine an arbitrary state that can be represented by x, y and z axes, positioned at the north pole of a sphere (Fig. 1a). Simply rotating the system around its z axis produces a gain of phase: a change in the orientation of the x and y axes, which can be represented by the angle of rotation of the x axis within the x–y plane.

However, to implement a two-qubit gate, the phase of the gate must depend on which states are adopted by the control and target qubits, and thus must be acquired in a fundamentally different way. If the system of axes is moved down the surface of the sphere to the equator, then along the equator for a short distance and back up to the north pole, the net result is again a rotation of the x axis (Fig. 1b). This phase change is proportional to the area enclosed by the pathway taken, and is referred to as geometric phase.

Returning to Schäfer and colleagues' work, the motion of a pair of ions along the pair's axis can be described in terms of two vibrational modes — one in which the ions oscillate in sync with each other, and the second in which they oscillate in opposite directions. Oscillation in these modes correlates the ions' positions and momenta, thus defining a 'phase space' for their collective motion and for geometric phase generation, analogous to the surface of the sphere mentioned above. The motion of the ions can be controlled using lasers, which induce a shift of the ions' electronic states that depends on the position of the ions. Position-dependent shifts of states also generate a force. Because the qubit of a trapped ion is encoded by electronic states, the force exerted on the ions by the lasers depends on the state of the qubit.

If two overlapped, coherent laser beams (that is, laser beams whose light waves are in sync) are used, they produce a standing wave. If the frequency of one of the lasers is tuned slightly away from the frequency of the other (corresponding to a frequency change of δ), then the standing wave starts to move. If δ is the same as the resonance frequency of one of the ions' vibrational modes, then the wave shakes the ions.

However, to induce geometric phase changes, δ must not be at the resonance frequency of the modes. At off-resonance frequencies of δ, the wave excites oscillations (phonons) of the trapped ions but then falls out of sync with those oscillations. After a period of time corresponding to half the amount of time needed for a gate operation, the same wave starts to decelerate the oscillation. Because the four electronic states corresponding to each of the four possible qubit combinations (00, 01, 10 or 11) couple to the lasers differently, the forces exerted on those states by the lasers are also different. The four states therefore move along different phase-generating pathways, so that the phase gain depends on the qubit combination. The phase information is then translated into qubit information by a simple operation that acts only on single qubits.

In previously reported two-qubit gates, ion displacement was performed adiabatically — the time taken for a displacement that induces geometric phase changes was long compared to the period of oscillation of the ions, limiting the operating speed of the gates[1,10]. Schäfer *et al.* have overcome this speed limit by shaping the amplitude of the laser pulses precisely in time, so that phase change is generated from pathways of a different shape from those used previously. The adiabatic situation is akin to adjusting the working of a pendulum clock by gently wobbling the clock. Schäfer and colleagues' method is like hitting the pendulum repeatedly with well-timed hammer strikes.

Remarkably, the strikes are calibrated to work correctly no matter where in its oscillation the pendulum happens to be. This makes the logic-gate operation robust to fluctuations of and within the strikes — the fluctuations might change the pathways taken to generate geometric phase changes, but they leave the areas enclosed by the pathways unaffected. Using their method, the authors speed up their gates sufficiently to challenge the dogma that trapped-ion, two-qubit gates are slower than analogous solid-state systems, such as those that use superconducting or silicon-based qubits.

It remains to be seen whether trapped-ion qubits (or qubits based on other platforms, or combinations of qubit types) can be sufficiently well controlled and used in large enough numbers to implement a universal quantum computer. Even if all operations were to have fidelities of 99.9%, a substantial number of additional qubits would still be required for quantum-error correction; these correction processes would take up additional computational time, slowing everything down. More experiments are needed in which gates are concatenated, to find out how this concatenation affects errors.

Schäfer *et al.* suggest that optimization of the parameters needed for the lasers, ion trapping and laser–qubit coupling will enable further speed increases and improve fidelities. However, classical computers will still be needed to control the protocols performed by quantum systems, and the speed limit for any qubit platform might be set by that classical computer. It should also be noted that all operations required for quantum computers will have different speed limits. Nevertheless, speeding up quantum logic gates, while at the same time mitigating or reducing the impact of most of the disturbances that affect them, is an excellent starting point for studying how the performance of quantum devices changes as their size increases, and potentially paves the way to a quantum computer. ■

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STEM CELLS

A gut feeling for cellular fate

A population of progenitor cells in the midgut of fruit flies undergoes differentiation in response to mechanical force. This finding marks the first time that such a phenomenon has been reported *in vivo*. SEE LETTER P.103

JACKSON LIANG & LUCY ERIN O'BRIEN

Over the past decade, advances in bioengineering have led to a newfound appreciation of the effects of mechanical force on stem cells. Micrometre-scale culture systems that can subject cells to highly specific physical deformations have allowed researchers to demonstrate that force can modulate stem-cell behaviours, and even prime stem cells for therapeutic transplantation[1,2]. However, even the most advanced culture systems merely approximate the complex and dynamic forces that stem cells experience in their native tissues. On page 103, He *et al.*[3] combine sophisticated genetic approaches and innovative physical manipulations to investigate the role of force on stem cells *in vivo*. They