Jim's bright idea

Everyone said James Franson was nuts when he proposed using light as the basis for a superfast quantum computer. Now they say he could be heading for a Nobel prize. *Rob Taylor* reports

THE LAB has the feel of the Cold War about it. At the entrance, security guards check guests for unauthorised cameras and recording devices. Foreign nationals must surrender their passports for ID checks. Even the cafeteria has a government-issue air about it.

This is the Applied Physics Laboratory, a department of Johns Hopkins University, set in 350 acres of rolling hills not far from Washington DC. Much of the research is funded by the US Department of Defense, and the work of James Franson is no exception.

The military are interested in Franson's work because he may have found a way to build superfast quantum computers that can carry out calculations impossible by any other means. The big problem with quantum computing is that any calculation is ruined if the particle carrying the information is disturbed in any way. So if you use electrons, atoms or ions to carry information, they have to be completely isolated, which requires all sorts of expensive equipment.

Light, on the other hand, is much less prone to unwanted disturbances. And it can be handled with simple equipment such as fibre optic cables, so it's ideal for carrying information. The trouble is that to actually make calculations, the information carriers have to interact—and under ordinary circumstances photons, the smallest possible bundles of light, simply ignore each other. This is why light rays pass through each other unaffected. Making photons interact turns out to be extraordinarily difficult.

But this is just what Franson aims to do. He has worked out that in certain circumstances, one photon can twist the polarisation of another. And he thinks he has a simple way to make it happen.

In a small lab across the hall from his tiny office, Franson is testing a simple device that could play the role of a quantum logic gate that uses photons as information carriers rather than the electrons used in conventional computers. Although researchers have been thinking about quantum computers for decades, nobody has come up with a way to mass-produce quantum logic gates. But if Franson can make his device work, quantum logic gates could become simple and cheap to make. And by combining lots of logic gates into a large-scale device, Franson hopes to become the first person to build a useful quantum computer.

The quantum world at the heart of Franson's work was discovered in the early decades of this century. Physicists found that the residents of this world are a strange bunch. Tiny bits of matter such as electrons and photons can behave as either waves or particles—depending on the way they are measured. They also jump instantaneously between clearly defined energy states without passing through any states in between. And they are harder to pin down than your boss at pay rise time. Heisenberg's famous uncertainty principle dictates that you can know properties such as a particle's energy or its position, but not both at once.

In the macroscopic world, however, quantum weirdness plays little or no part, and useful devices that depend on the antics of quantum particles are few and far between. But in 1985, a physicist at Oxford University called David Deutsch worked out how quantum particles could carry information and how a quantum computer could use this information to carry out calculations. Since then other researchers have fleshed out how such a machine could solve real problems. It turns out that quantum computers can solve problems that today's computers could never crack. Building one would be a major advance.

A quantum computer performs its prodigious feats by taking advantage of another strange characteristic of the Universe on the smallest scale. Quantum particles can exist in two or more states at the same time. This is as strange as a football being in two places at the same time. When this happens, physicists say the states are superposed. Electrons, for example, can exist in more than one energy level at the same time. And photons can exist in two orientations of polarisation at the same time. Only when pressed by some kind of outside interaction or measurement does the particle choose one state or the other.

Some physicists even talk about a particle in such a superposition of states being in two different universes. In each universe, the particle is in a different state. When a measurement is made on the particle, this house of cards collapses. One universe is destroyed while the other is spared.

In a quantum computer, these states represent the 0s and 1s of a digital code. The revolutionary idea is that when a particle is in a superposition of states, it can represent both a 0 and a 1 at the same time. This strange bit of quantum information is known as a qubit.

Calculations are made by passing the qubit through a series of logic gates. In one universe the calculation occurs as if the bit is a 0 and in another universe as if it is a 1. With several qubits, a computer could carry out large numbers of calculations in many different parallel universes. In fact, the number of calculations that are possible rises exponentially with the number of qubits.

Parallel universe

"People in regular computing talk about parallel processing, in which a problem is broken up into pieces that are fed simultaneously to multiple processors," says John Dowling, a researcher in quantum optics at the US Army Aviation and Missile Command at the Redstone Arsenal in Huntsville, Alabama. "In quantum computing you do the same thing, but the other computers happen to be in different universes. It sounds strange, but that's what quantum mechanics is like."

Physicists have even demonstrated the principles of quantum computing using single ions and the spin of individual atomic nuclei as qubits. But making a machine with enough qubits to do anything interesting is a different matter. "People are confident they can make a two-qubit quantum computer, or maybe one with 10 qubits," says David DiVincenzo of IBM's Watson Research Center near New York. "But even the most optimistic researchers tend to get a little pale if you ask for 50."

So making a quantum computer that can do much more than count its fingers and toes is extremely difficult. The problem is that particles in a superposition of states are extraordinarily sensitive to outside influences. The slightest nudge causes them to collapse back into a single state, ruining any quantum calculation before it is complete.

Somehow qubits have to be protected from unwanted nudges. But this is particularly difficult when the qubits have to pass through logic gates. An electron passing through a material remains in a superposition of states for less than a nanosecond, nowhere near enough time to carry out useful calculations.

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Photons have far more potential. For a start, it's quite easy to use their polarisation to represent the zeros and ones of binary code—a horizontally polarised photon might represent a zero, for example, while a vertically polarised photon represents a one. And photons are easy to control using optical fibres. Most important of all, they are relatively undisturbed by the world around them. In a vacuum, almost nothing bothers photons. Put them in an transparent optical fibre and photons can remain coherent for a millisecond or longer—more than a million times as long as electrons remain coherent.

But photons present difficulties as well. Because they never sit still, photons are hard to store, although this could be overcome by passing them through long fibres. But the biggest problem is that they do not easily interact with each other. Without a strong interaction, logic gates simply do not work. This is where Franson's ideas come in.

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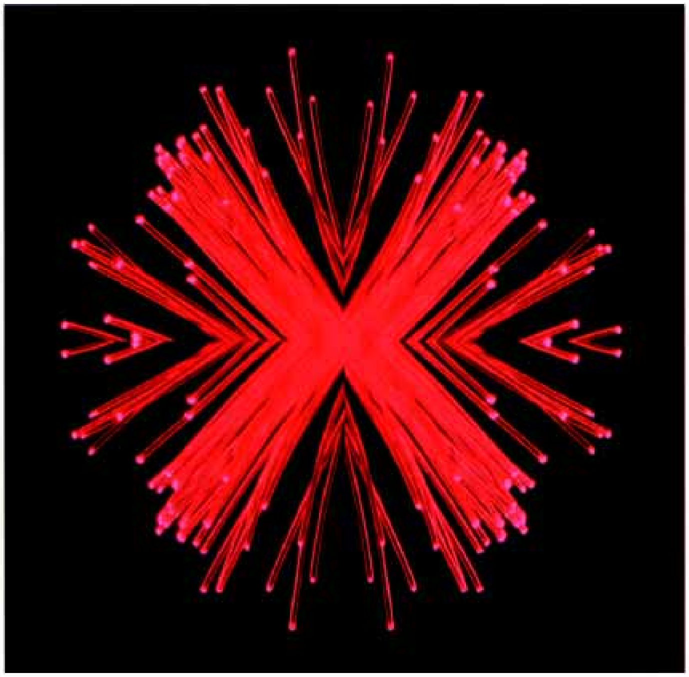
One of the features of a logic gate is that its output depends on the bits coming in. In a device known as a conditional-not gate a bit will be flipped from a 0 to a 1, or vice versa, if the incoming bit is 1. Since all other types of logic gates—and thus a quantum computer—can be built out of combinations of conditional-not gates, they are the only kind that physicists need worry about.

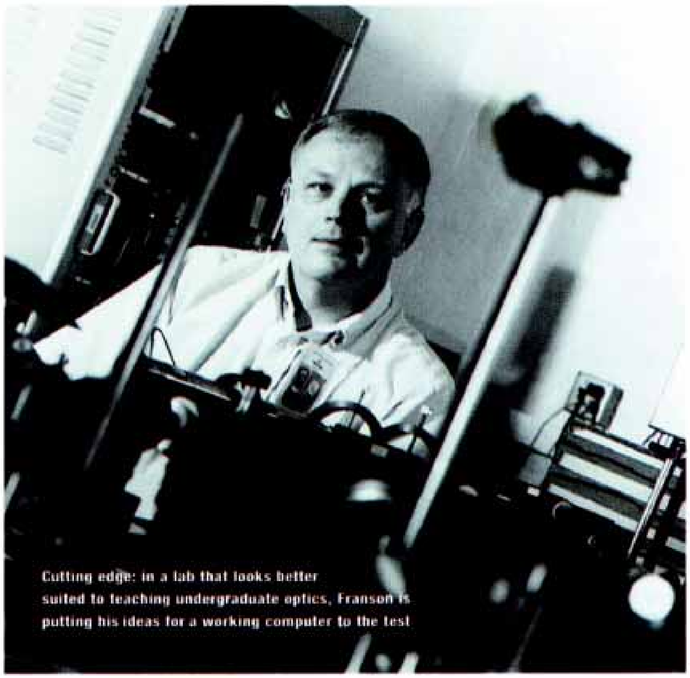
So if photon-based logic gates are ever to work, physicists must find a way of twisting the polarisation of one photon by 90° if and only if another photon that enters at the same time is, say, vertically polarised. What's more, a quantum computer that packs a decent punch will only be practical if these gizmos are relatively simple, reliable and easy to link together.

The starting point for Franson's theory is a well-known phenomenon called the Kerr effect. Normally, two beams of light ignore one another when they cross. But in certain crystalline substances called Kerr materials they can interact. If one beam is bright enough, it changes the refractivity of the material—how it bends light entering it—and this, in turn, changes the polarisation of the second beam.

On the atomic scale, a photon from the first beam excites an atom and the excited atom then twists the polarisation of a photon from the second beam. Of course, the first beam of light must be intense enough to excite most of the atoms most of the time in case any one of them is struck by a photon from the second beam. This hit-and-miss affair makes the traditional Kerr effect unsuitable for a quantum logic gate involving only two photons.

But Franson realised that a Kerr-like effect might be possible with only a single pair of photons, and that under certain circumstances this effect could become magnified until it was large enough to be measured. Once again, the idea relies on quantum mechanics. First, by defining the wavelength of each photon precisely, it becomes impossible to pin down its location. This is Heisenberg's uncertainty principle, and the result is that photons become "smeared" throughout the substance they are travelling through. So when a particular





Cutting edge: in a lab that looks better suited to teaching undergraduate optics, Franson is putting his ideas for a working computer to the test

photon interacts with an atom in the substance, it is impossible to know which atom the photon interacted with.

Now imagine two photons with slightly different wavelengths, A and B, passing through a medium. Of the many different ways that these photons can interact with matter, Franson is interested in only one. This is the case when one atom in the medium absorbs the photon with wavelength A and emits one with wavelength B while another atom some distance away absorbs B and emits A. The rules of quantum mechanics dictate that this process of photon-swapping changes the polarisation of the photons by a tiny amount. However, this change is normally too small to measure.

But Franson has spotted a trick that can magnify the effect. It depends on the fact that it is impossible to say just which pair of atoms have exchanged the incoming photons. "Instead, you are left with a bunch of mutually indistinguishable possibilities," he says. "The laws of quantum mechanics dictate that in this circumstance, each possible exchange contributes to the overall effect." In fact, the effect is magnified in proportion to the square of the number atoms in the sample. And because even a small amount of matter contains huge numbers of atoms, the overall twist put on the second photon becomes big enough to be useful. This, at least, is the theory that Franson published in *Physical Review Letters* last year (vol 78, p 3852).

Photon trap

For the moment, other physicists are reserving judgment. A year and a half earlier, physicist Jeff Kimble and his colleagues at the California Institute of Technology in Pasadena had used a different method to achieve something similar, that is, to make one photon alter the state of another.

The heart of Kimble's method is a trap for photons—a tiny cavity between surfaces so reflective that the photons bounce back and forth about 100 000 times before escaping, greatly magnifying their interaction with the single caesium atom that Kimble and his colleagues drop into the trap along with the photons.

Kimble's approach is extremely demanding. Working with individual photons and atoms and with the world's most highly polished mirrors isn't easy. "Our experiment is a technically daunting enterprise," says Kimble, "and there is still a frightful gulf between lab

Quantum logic gate

Light fantastic:
the polarisation of photon A twists
if photon B is vertically polarised but not if B is horizontally polarised

demonstration and any useful implementation. Jim [Franson] has come up with a really clever way, at least in principle, to avoid the complexity of needing to use just one atom and an optical trap. It remains to be seen if he is right."

With his theory published, Franson, has shifted his focus to the lab and begun the hunt for experimental confirmation aided by Todd Pittman, a postdoctoral fellow at the Applied Physics Laboratory. Another modest place, their lab looks better suited to teaching an undergraduate optics course than carrying out cutting edge quantum physics research. It is dominated by a light table, a kind of oversized billiard table housing a forest of lenses and mirrors. The entire setup is run by a 15-year-old Apple IIe computer tucked against the wall. "It still works fine and it's easy to program," says Franson, clearly a practical man.

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Franson has chosen to pass his photons through sodium vapour housed in a glass cell a couple of centimetres long. He and Pittman start with two photon beams, each with a slightly different wavelength, but close to an excitation frequency for sodium. First, they carefully filter out all but the right wavelengths, circularly polarise the first beam and plane polarise the second, then attenuate the beams until only a small number of each kind of photon is passing through the cell. On the other side of the cell, Franson has detectors for the two kinds of photons. Finally, he puts a polarising filter in front of the detector for the second wavelength of photon.

Every now and then one of each kind of photon happens to pass through the cell at the same moment. According to his theory, the polarisation of the second kind of photon should become twisted when this happens. Franson looks for this rotation by using the polarising filter in front of the second detector to block any photons that have not been rotated.

The data he collects are statistical, counts of how many times two photons reach the detectors at the same moment. Since all unaffected photons should be blocked before they hit the second detector, there would be no events to count if there were no rotation. But Franson has spotted a few photons coming through and has worked out that this corresponds to a rotation of about 3°.

The results are encouraging although not yet conclusive. Franson still has to show that the observed effect varies in the way his theory predicts. For example, the effect should vary in a specific way with the density of sodium atoms inside the cell. Franson is looking for this effect and says that he should have more definitive results within six months.

Earlier this year, he presented his initial data at a NASA-sponsored conference on quantum computing in Palm Springs, California. His colleagues were sceptical, but less so than they were when he published his theory. "When Jim first started talking about this a couple years ago, almost everybody said he was nuts," recalls Dowling. "People asked things like: 'How come nobody has seen this before? How come it's not in the nonlinear optics textbooks?'"

All that has changed. Now physicists are waiting to see if he is right. "Jim has a pretty good track record on other things. And if he's right, it will help all of us make the quantum computer we're trying to make," says Dowling.

Code cracker

Even if Franson is right, a useful quantum computer is still years away. But Franson, in characteristic style, is already thinking about how to move beyond his somewhat bulky glass sodium vapour cells to a more practical solid-state device. "It might be possible to connect 100 000 of these things up in a warehouse somewhere, if that's what it took," he says. "But our goal is to switch to solid state crystals, which could be very small." His idea is to use optical fibres, or optical waveguides etched onto a silicon crystal, to connect the logic gates together. The result would resemble a standard computer chip.

One organisation that might be willing to back the construction of a warehouse-sized computer is the National Security Agency, a secretive US government organisation which already supports Franson's work.

The NSA is interested in cracking codes, a problem that quantum computers should be particularly good at. Many codes are based in the fact that it is easy to multiply two large prime numbers together to get a much larger number, but very difficult to start with the large number and find the two primes that produced it. Quantum computers ought to be able to do this in a tiny fraction of the time an ordinary computer might take.

And if Franson is right, quantum computers might not be that far off. For the moment, physicists are curious to see if Franson comes up with the experimental evidence he needs. "Will Jim's device be a panacea enabling large-scale quantum computing? Nobody can tell," says Kimble. Dowling is more confident: "If he's right, I think he'll win the Nobel prize, for sure." □

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