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Department of Physics Newsletter

UNIVERSITY OF OXFORD

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QUANTUM COMPUTING

I will begin this introduction on a personal note. I got interested in quantum computing because I was already interested in quantum physics and in computing. I was intrigued by not just quantum superposition, but, more significantly, quantum *entanglement*. And I found the idea of the *Turing machine* fascinating, and I enjoyed programming. What is important about quantum computing is not simply that it offers a new way to do computing, but also, and in my opinion this is more significant, it shows us an insightful way to think about the fundamental principles of physics.

Much of physics has been involved with discovering basic laws: Newtonian mechanics, then relativity and quantum mechanics, and more recently chromodynamics and the Standard Model. This might be compared to discovering theorems in mathematics. However, at the turn of the twentieth century, mathematicians were thinking about another type of question. Instead of asking, 'is such-and-such a theorem true?' they wanted to ask, 'is it the case that all theorems are susceptible to proof or disproof?' This 'stepping back' into a larger type of question is called framing a 'meta-question'. It was by asking such meta-questions that mathematician Alan Turing opened up the foundations of computer science, with significant help from others such as Kurt Gödel, Alonzo Church and John von Neumann.

Much of physics is involved in discovering the 'rules of the game' for systems more complicated than small collections of fundamental particles, such as bulk condensed matter, fluid dynamics and the like. However, we can instead ask a different type of question, more like the mathematicians' meta-question: supposing we know the basic rules, what sorts of games can be played? By merging information theory with quantum theory, we have learned how to ask questions like that in useful ways, as I will elaborate.

1 QUANTUM COMPUTER

A good way in to the subject is to describe a quantum computer, and then discuss what sorts of things one can do with it. It will then become clear how it both allows interesting computations that could not easily be done any other way, and also allows us to explore meta-questions about the physical world.

1.1 Quantum bits

Quantum computing is, to put it simply, a form of information processing based on complete control of a physical system, where, by 'complete', we mean complete. Once we have isolated which part of nature is the physical entity to be used to carry out a computational process, there must be no degree of freedom left uncontrolled or unknown in that entity. The simplest way to envision this is to take as our computing system a line of atoms. Each atom has internal and external degrees of freedom (the electronic state, and the motion, respectively); all must be under experimental control, not subject to thermal or other noise.

We will take it that each atom has a ground state with total spin half, and we can manipulate the direction of the spin vector by applying laser or microwave pulses. You can imagine each atom as like a tiny magnet, whose spatial orientation can be rotated by such pulses. We assign the label 0 to the state where the magnet (or the spin angular momentum) is pointing straight down, and the label 1 to the state where the magnet is pointing straight up, and thus we have a simple form of binary memory, with one atom per bit. We shall refer to these atoms as 'quantum bits' or qubits. One can already see that there is more to them than classical bits, because there are more states available to them than simply 0 or 1 (down or up): they can point in any direction. However, so far there is nothing particularly remarkable to report. It is not significantly different from using classical things, such as little arrows made of wood, to do information storage.

1.2 Quantum gates

Next we suppose that these atoms can also be subject to a quantum process called a *two-qubit logic gate* or *quantum gate*. For example, we apply a sequence of laser pulses to a pair of neighbouring atoms, such that they evolve together (as described by Schrödinger's equation) in such a way that the evolution of the second depends on the initial state of the first. A good example is the *controlled-not* gate, in which the second atom experiences a rotation through 180 degrees about a horizontal axis, if and only if the first atom was initially in the state 1. Thus we implement a simple example of binary logic. An arbitrary quantum state of a pair of atoms is some general combination of the states $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$:

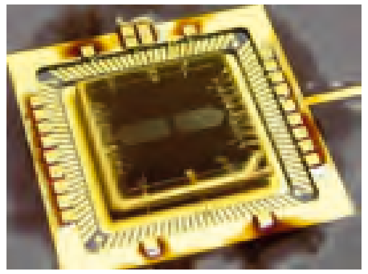
$$a\,|00\rangle + b\,|01\rangle + c\,|10\rangle + d\,|11\rangle \qquad (1)$$

where a, b, c, d are complex coefficients. Under the controlled-not gate, each part evolves according to the logic: $|00\rangle \to |00\rangle$, $|01\rangle \to |01\rangle$, $|10\rangle \to |11\rangle$, $|11\rangle \to |10\rangle$, so the outcome in this example would be

$$a\,|00\rangle + b\,|01\rangle + c\,|11\rangle + d\,|10\rangle\,. \qquad (2)$$

Another important two-qubit gate is called *controlled-z* or *controlled-phase*; it has the 'logic table'

Prof Andrew Steane



Above: Microchip under development in Oxford for an ion-trap based quantum computer. Oscillating voltages on the thin gold electrodes cause a line of calcium ions to be held suspended in ultra-high vacuum just above the surface of the chip. Tightly focussed laser beams address the ions from the side, and microwave pulses are implemented via the electrodes.

$|00\rangle \to |00\rangle$, $|01\rangle \to |01\rangle$, $|10\rangle \to |10\rangle$, $|11\rangle \to -\,|11\rangle$. If we apply this to the outcome (2) then the state evolves to

$$a\,|00\rangle + b\,|01\rangle - c\,|11\rangle + d\,|10\rangle\,. \qquad (3)$$

This illustrates an important point. In the notation we have adopted, all that happened here is a sign change in part of the superposition, but this is a significant change in the quantum state. The phases of the complex coefficients appearing in the state are important. One designs quantum algorithms – sequences of logic gates – in such a way that some of the computational paths come together and interfere constructively, others destructively, and such interference effects depend crucially on the phases.

1.3 Quantum algorithms

A 'quantum algorithm' in general is a process having the form 'input, manipulate, output,' in which the input consists of preparing a set of qubits in a simple state such as all 0 or 'down', the manipulation consists of a sequence of quantum logic gates applied to the qubits, and the output is obtained by measuring their final state. That is the essential idea, but there is a further subtlety, because not all such processes deserve the epithet 'quantum,' even though qubits may be involved. We are only really interested in algorithms that exploit the subtleties of quantum physics, especially quantum *entanglement*, in such a way as to produce an outcome more efficiently than could be done by traditional or 'classical computing' methods.

It turns out that some very powerful such algorithms exist. The most famous is Shor's algorithm, which is designed to compute the period of a periodic function. This can be used, via some further (ordinary, classical) computing to find the prime factors of a composite integer. Even in the absence of Shor's algorithm, one can already guess that quantum computers might be powerful, simply because they manipulate quantum states. If one has n qubits, then the quantum state has 2^n parts, and in order to simulate the quantum process using ordinary computing, one would have to manipulate 2^n complex numbers. For example, for $n = 100$ (a modest number of atoms), this is $2^{100} \simeq 1.27 \times 10^{30}$ complex numbers. That would require about 10^{18} terabytes of memory. This exceeds the total capacity of all computer facilities in the world by a factor $> 10^9$.

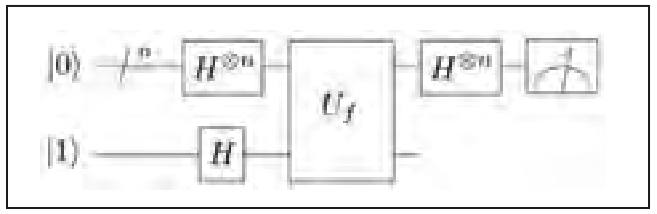
However, the way to think about quantum computing is not in terms of memory but in terms of algorithm efficiency. In order to observe the outcome of a quantum computation, one measures each atom separately. For example, in a fluorescence method, one excites each atom to an electronic excited state, in such a way that it glows (scatters many photons) if it was found in state 1, and remains dark (scatters no photons) if it was in state 0. By reading off the sequence of glowing dots using a camera, one reads the binary number, which is the output of the calculation.

Just before this final measurement or output step, there will often be a superposition involving both down and up (0 and 1) for any given atom. In this case, following the standard theory of measurement in quantum mechanics, at the measurement the atom adopts one of the states down or up, with a probability given by the square of the relevant coefficient or quantum amplitude in the superposition. The outcome is not completely random because not all the atoms need be in such a superposition, and those that are have well-defined probabilities to adopt one final state or the other.

In the final measurement, only one term in the possibly vast quantum superposition is revealed, so it is no use trying to use such superpositions for data storage and retrieval. Instead, one does something more clever. One looks for mathematical or algorithmic tasks in which a large number of intermediate results may be involved, but the final outcome only consists of a small collection of numbers, or even just a single number. This might furnish, for example, some global property of the intermediate results, such as their average or their minimum or their period. If a classical computer could compute the same result only by working through the intermediate results one at a time, it could do it, but it would take prohibitively long. For example, suppose a quantum computer plodded along at one quantum gate per second, while a classical machine might achieve 10^{18} classical gates per second. The quantum computation on 100 qubits could finish in minutes or hours, while the classical machine trying to simulate it would take about 40000 years just to do one operation on each of the 2^{100} cases.

1.3.1 Example: the Deutsch algorithm

In order to make all this a little more concrete, let's look at one example of a simple algorithm called *Deutsch's algorithm*. The idea of the algorithm is as follows. Suppose we have some function $f(x)$, and all we want to know is whether or not $f(0) = f(1)$. To keep things simple, we only consider functions



Right: The Deutsch-Jozsa algorithm. The diagram shows a sequence of operations on n+1 qubits, with, hidden inside the box marked 'U_f', possibly a large logic network involving many further qubits and operations. This computes the function $f(x)$ under investigation. The boxes marked 'H' rotate the qubits, and finally the upper qubit is measured. Time evolves from left to right. Note that the U_f network is only needed once.

whose value is either 0 or 1 at $x = 0$ and $x = 1$. For example, if $f(x) = \cos(2\pi x)$ then $f(0) = f(1) = 1$, and if $f(x) = \sin(2\pi x)$ then $f(0) = f(1) = 0$ so both of these satisfy $f(0) = f(1)$. On the other hand, if $f(x) = \cos(\pi x/2)$ or $f(x) = \sin(\pi x/2)$ then $f(0) \neq f(1)$. In general, the function f might be hard to compute. Modern computers can compute trigonometric functions very quickly, but it is easy to find functions that it would take years to compute by ordinary methods. The quantum computer offers a way to find out whether or not $f(0) = f(1)$ in the time that it takes to evaluate the function just once.

In Deutsch's algorithm, we start with two qubits in the state 'down, down', or $|0\rangle\,|0\rangle$. We then rotate them both about a horizontal axis (the y axis), one by 90°, the other by −90°, which produces the state

$$\begin{aligned} &\frac{1}{2}\big(\,|0\rangle + |1\rangle\,\big)\big(\,|0\rangle - |1\rangle\,\big) \\ =\; &\frac{1}{2}\big(\,|0,0\rangle - |0,1\rangle + |1,0\rangle - |1,1\rangle\,\big). \end{aligned} \tag{4}$$

Now we consult our classical computer-science colleagues, asking them for a logic gate network that can compute $f(x)$ using traditional classical logic (AND-gates, OR-gates and the like), or we figure one out for ourselves. Then we translate this network into one using quantum gates. This involves some careful replacements, because AND and OR are not directly available; we need the whole network to be reversible or *unitary*, a technical detail that I will not elaborate here. Suffice it to say, it can be done, and the resulting quantum network is similar in size (and therefore in execution time) to the classical network that it replaces.

Such a network can be used to cause the simple-looking (but actually quite lengthy) evolution $|x\rangle \to |f(x)\rangle$, where x is equal to either 0 or 1. Once we possess this network, one can show that it is not difficult to extend it to a network that acts on two quantum bits and causes the evolution $|x\rangle\,|y\rangle \to |x\rangle\,|f(x) \oplus y\rangle$ where $\oplus$ is addition modulo 2. Applying such a network to the state (4), one obtains

$$\frac{1}{2}\Big(\,|0,\alpha\rangle - |0,\alpha\oplus 1\rangle + |1,\beta\rangle - |1,\beta\oplus 1\rangle\Big)\,. \tag{5}$$

where $\alpha \equiv f(0)$ and $\beta \equiv f(1)$. Since we agreed only to consider functions where α and β are either 0 or 1, there are only four possible outcomes to consider. The combination in the bracket in (5) is one of the following:

$$\begin{array}{ll} \alpha,\beta & \\ 0,0: & |0,0\rangle - |0,1\rangle + |1,0\rangle - |1,1\rangle \\ & = (|0\rangle + |1\rangle)\,(|0\rangle - |1\rangle) \\ 0,1: & |0,0\rangle - |0,1\rangle + |1,1\rangle - |1,0\rangle \\ & = (|0\rangle - |1\rangle)\,(|0\rangle - |1\rangle) \\ 1,0: & |0,1\rangle - |0,0\rangle + |1,0\rangle - |1,1\rangle \\ & = -\,(|0\rangle - |1\rangle)\,(|0\rangle - |1\rangle) \\ 1,1: & |0,1\rangle - |0,0\rangle + |1,1\rangle - |1,0\rangle \\ & = -\,(|0\rangle + |1\rangle)\,(|0\rangle - |1\rangle) \end{array} \tag{6}$$

Finally, we rotate both qubits through 90° about the y axis, which causes

$$2^{-1/2}\big(\,|0\rangle + |1\rangle\,\big) \to |0\rangle \text{ and } 2^{-1/2}\big(\,|0\rangle - |1\rangle\,\big) \to |1\rangle$$

(note the role of the interference phase here). The outcome, in the four cases, is

$$\begin{array}{lr} \alpha,\beta & \\ 0,0: & |0\rangle\,|1\rangle \\ 0,1: & |1\rangle\,|1\rangle \\ 1,0: & -\,|1\rangle\,|1\rangle \\ 1,1: & -\,|0\rangle\,|1\rangle \end{array} \tag{7}$$

One finds that the second qubit finishes in the same state in all four cases, therefore we may as well ignore it from now on. It has served its job as temporary memory; the 'output' is now in the first qubit. We finish by measuring the first qubit, for example by the fluorescence method. The overall sign in front of the whole state does not influence this measurement outcome. Notice what is found: the cases $\alpha = \beta = 0$ and $\alpha = \beta = 1$ both produce the outcome '0' or 'down' or 'atom did not glow'. The cases $\alpha \neq \beta$ both produce the outcome '1' or 'up' or 'atom did glow'. So the observation of whether or not the first atom finally glowed tells us, unambiguously, whether or not $f(0) = f(1)$. And (here is the crucial part): *we only needed to operate the network to calculate f (x)* once!

This simple idea was soon extended by David Deutsch and Richard Jozsa to the *Deutsch-Jozsa algorithm*, in which the function f still produces only 0 or 1 as output, but now takes n qubits as input. There are now 2^n possible values of x, and one considers functions which, when plotted as a function of x, produce either a flat line (always 0, or always 1), or which evaluate to 0 for some x, and 1 for other x, with equal amounts of each, such that the average value is 1/2. If one wanted to know which type of function one is dealing with, and had no other information, then the only way to proceed, classically, would be to compute the function on at least $2^{n-1} + 1$ values of x, in order to be sure of telling whether or not it changes somewhere. The quantum algorithm requires only a single operation of the network to compute $f(x)$. Thus we have an example of an 'exponential speed-up'.

The quantum computation on 100 qubits could finish in minutes or hours, while the classical machine trying to simulate it would take about 40000 years just to do one operation on each of the 2^{100} cases.

The ideas on show in the Deutsch-Jozsa algorithm have something of the same flavour of those exploited in a more sophisticated way in Shor's algorithm. We sometimes say the method works because the quantum computer in some sense evaluates $f(x)$ on all 2^n values of x simultaneously, or 'in parallel'. This is a good insight as long as one does not over-state the interpretation; this is not like classical parallel computing because these intermediate results are not all available to be read out. Indeed they are erased during the step in which the interference happens. We have now gone a long way away from the simple picture of a line of little wooden arrows.

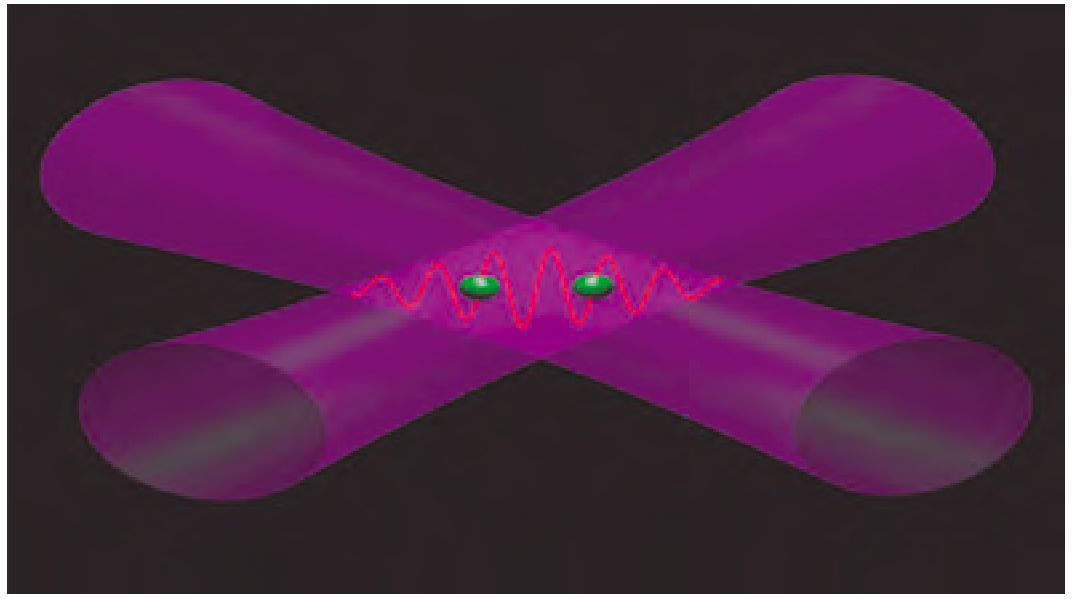
2 UNIVERSALITY

Now let's return to the question, 'what kind of things are possible in quantum mechanics?' We can begin to answer this using a quantum computer, because of the concept of *universality*. In classical computing, one computer can simulate another, and this is an important general idea. It carries over to quantum computing because the laws of quantum physics describe all systems equally well. One quantum system can be used to compute another, because they can all be reduced to the language of state vectors in Hilbert space. What is more profound, however, is that such simulation is efficient, in a technical sense. The simulator does not need to be a lot bigger than the simulatee, and, for systems with local Hamiltonians, the number of quantum gates required is not excessively larger than the number of basic processes being simulated. Making these concepts precise was one of the major contributions of David Deutsch. It turns out, also, that we don't require a large collection of different basic operations (logic gates) in order to arrive at a universal computer. The simple rotations and two-qubit controlled-not gates that I have already described would be sufficient, for example. This is a non-trivial and interesting result.

One of the implications of universality is a certain flexibility about how quantum computing can be conceived. I have described above the basic 'network model' where we envisage a set of qubits evolved by a pre-determined sequence of logic gates. There are other models, such as 'adiabatic quantum computing' where one slowly adjusts the nature of the interaction of each qubit with its neighbours, and the beautiful 'graph-state' or 'one-way' computer where one starts from a special and highly entangled state of all the qubits, and then applies judiciously chosen single-qubit measurements and rotations. One can show that each of these computer models can simulate the others efficiently, so they have equal computing power. This in itself is a profound insight into the physical world. It suggests a variety of ways of interpreting the computational process, and it also offers different options to the experimenter who is trying to build a machine.

3 PRACTICALITY

The practical difficulty of quantum computing, and it is extremely difficult, is to get the required degree of precise control over the qubits. The atoms tend to rotate a little, in unwanted, unpredictable ways, owing to magnetic field noise, for example. But we need them to 'behave' – maintain a predictable direction in space – over thousands or perhaps millions of operations. A quantum algorithm involving N qubits and Q operations requires each gate to be precise to the level $\sim 1/Q$ and each qubit to stay in a precise direction to the level $\sim 1/NQ$. With much effort, one can imagine these precisions reaching parts per thousand for the operations, and parts per million for the memory. So this limits the size of algorithm one can practically contemplate to perhaps 1000 operations and 1000 qubits. That would already be significant (it is not yet achieved but looks feasible), but for problems such as Shor's algorithm one would want a larger machine. This is where another fascinating idea called *quantum error correction* comes into play. But that is another story. ■



Right: A two-qubit quantum logic gate can be performed by a pair of laser beams which produce an oscillating force on a pair of electrically charged atoms. The magnetic dipole of each atom plays the role of qubit and also dictates the direction of the resulting force.

The newsletter production team would like to thank Marein Rahn for his assistance in producing this article.

KNOTS, WORLD-LINES, AND QUANTUM COMPUTATION

At a few points in modern human history, scientific goals that seem overwhelmingly difficult have nonetheless been achieved by an enormous concerted efforts of many scientists. The atomic bomb project and the Apollo space programme were two such examples. The dream of developing a quantum computer is another such seemingly overwhelmingly difficult goal, which looks like it might be achieved someday soon.

As discussed by Andrew Steane in his article 'Quantum Computing' (see page 5), the key challenge of building a quantum computer is that they are exceedingly sensitive to errors from small amounts of noise in the environment. While a few approaches have been proposed for addressing this problem, there is one particularly appealing approach, which invokes a connection between quantum properties of certain fundamental particles, and the mathematical theory of knots. This article will explore these connections and describe how they might help overcome the key challenge of building a quantum computer.

KNOTS AND FUNDAMENTAL PARTICLES

A knot is nothing more than a piece of tangled string with the ends reconnected so that there is no end to the string (see examples in Fig. 1). To understand the connection between knots and fundamental particles, we must remind ourselves of two basic ideas that grew from thinking about relativity. First, space and time should be treated mostly on the same footing. If an object moves back and forth along a one dimensional horizontal line, to describe the motion of this object we can draw a two-dimensional 'space-time diagram', which simply plots the position of the object (in the horizontal direction) as a function of time (plotted along the vertical direction). The line which describes the position versus time is known as the 'world-line' of the object, since it tells you where in the world the object is at any given time. Similarly, if an object moves around horizontally in two-dimensions (say, the object is confined to the surface of a table) we could draw a three-dimensional space-time diagram – with two dimensions of space (in the horizontal directions) and one dimension of time (drawn in the vertical direction). The world-line of an object would look like a string living in three dimensions. If two different objects were to move around each other on the two-dimensional surface, their two world lines would wrap around each other, in a way reminiscent of forming a knot.

The second, related, basic principle comes from Einstein's famous equation $E=mc^2$. This tells us simply that mass and energy are the same thing. Every particle of matter has mass, and each such particle of matter has a corresponding particle of antimatter, which has exactly the same mass. However, if the matter and corresponding antimatter particles are brought together, they can annihilate each other, turning their mass into energy, which is usually emitted in the form of light. The process can just as well occur in reverse: if energy is put into a system, say in the form of light, the energy can be absorbed and turned into mass by creating a particle-antiparticle pair.

Using these basic principles one can consider space-time diagrams like the one shown in Fig. 2. Here we are considering particles that move in two dimensions (horizontal) and time is plotted in the vertical direction. In this picture, at an early time, energy is put into the system to create two particle-antiparticle pairs. One particle moves around another antiparticle, and then the two particle-antiparticle pairs are brought back together again to annihilate each other, re-emitting their energy. Clearly in this case we have created knotted world lines.

IMPORTANT PHYSICAL EFFECTS

So for particles that move around in two dimensions, it is easy to imagine how world lines can become knotted. What is not so obvious is that the knotting of world lines can have important physical effects. Here is the surprising fact: in two dimensions, certain particles, called *anyons*, exist, where the physical properties of the particles depend on the knots that their world lines have formed in 2+1=3 dimensional space-time. In particular, depending on the knot that has been formed, the particles may or may not be able to annihilate another particle at the end of the knot. This is rather surprising since one rarely thinks that any property of a particle should depend on its history. Furthermore, these effects are very nonlocal in both space and time: for example, in Fig. 2, the two particles that wrap around each other may never have even been spatially close to each other, but if one's world line wraps around the others, it can become physically altered – so that it no longer can annihilate with its antiparticle.

Since the properties of a particle depend on the space-time knots that have been formed by its world lines, it is crucial to be

Prof Steve Simon

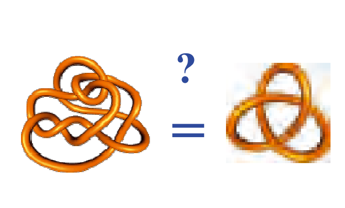


Fig. 1: Two knots. Can they be deformed into each other without cutting any of the strands?

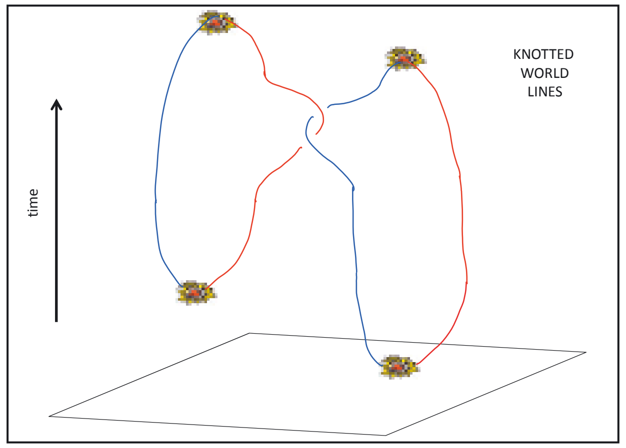


Fig. 2: A space-time diagram in two dimensions (horizontal) and time (vertical). In this diagram, the world lines of particles form a knot. The yellow flashes at the bottom and top indicate the creation and annihilation of the particle-antiparticle pairs.

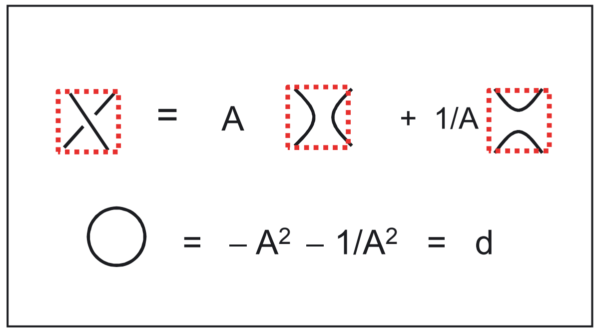


Fig. 3: The rules of the Kauffman knot invariant algorithm (Kauffman Bracket, essentially equivalent to the Jones Polynomial).

able to distinguish different knots from each other. We generally need to know if the two knots can be deformed into each other without cutting any of the strands. If two knots can be deformed into each other, then we say they are equivalent knots – otherwise we say they are inequivalent (two equivalent space-time knots will produce equivalent particle properties at the ends of the knots). While it might sound simple to determine whether two knots are equivalent, it can be quite hard if the knots are complicated. In fact, determining the equivalence or non-equivalence of knots remains a modern topic of mathematical research.

KNOT INVARIANT

Fortunately, mathematicians have developed a useful tool known as a 'knot invariant' that can help distinguish knots from each other. A knot invariant is nothing more than an algorithm that takes a knot as an input and gives some mathematical expression as an output. The key to being a knot invariant is that two knots which can be deformed into each other without cutting any of the strands must give the same output. So if you have two knots and you don't know if they are equivalent or not, you put them into the knot invariant algorithm and if they give different outputs you know immediately that the knots are inequivalent – they cannot be deformed into each other without cutting.[1] An example of such a knot invariant algorithm, the so-called Kaufmann invariant[2], is shown in Fig. 3.

> String theorist Ed Witten was awarded a Fields medal, along with Vaughan Jones, for work elucidating the connection between knots and quantum physics.

Roughly, one begins with a diagram of a knot. Then one applies the crossing rule to each over- or under-crossing of strings as shown in the first line of Fig. 3. Each time you apply the rule, you obtain a sum of two diagrams with appropriate coefficients of the variable A and A^{-1}. Eventually you obtain diagrams with no crossings of strings, in which case each loop can be replaced by the variable d, as shown in the lower line of Fig. 3. To see how this works we evaluate the Kauffman invariant of a very simple knot in Fig. 4, see the inset box for the details of the calculation.

In this simple calculation we started with the figure 8-like knot in the upper left of Fig. 4. It is easy to see that this knot is just a simple loop of string that has been folded over to make it look like a figure 8. Applying the Kauffmann algorithm to this knot yields an end result of 'd'. This is as it should be, since the original knot was just a simple loop of string, it should have a Kauffman invariant value of 'd' (this is the second rule of the Kauffman invariant in Fig. 3). As long as the knot was not cut at any point, the result should still be 'd'. We could have folded the knot over many many times and

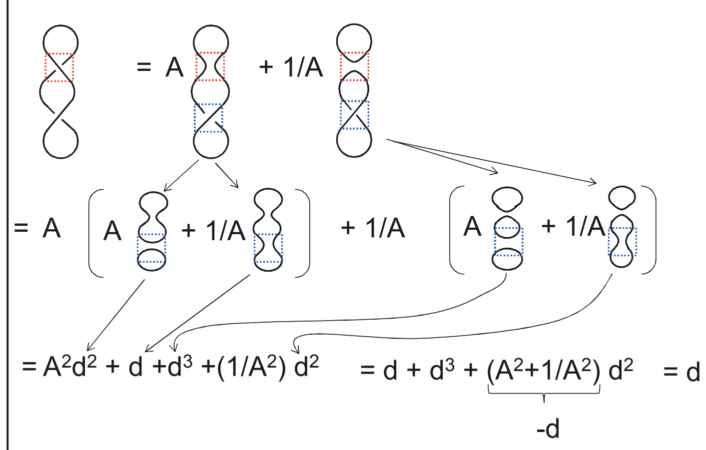
1 Unfortunately two inequivalent knots may also give the same output in certain cases. The knot invariant can sometimes tell you with certainty that two knots are different, but they typically cannot tell you with certainty that two knots are the same.

2 The Kauffman invariant is essentially the same as the famous Jones Polynomial knot invariant. The mathematical discovery of this knot invariant was important enough that it won the Fields medal (the highest prize in mathematics) for its discoverer, Vaughan Jones. Louis Kauffman simplified Jones' work so that it is understandable to the rest of us!

The evaluation of the Kauffman invariant of the knot in the upper left of Fig. 4.

We start by focusing in on one of the crossings of our knot, in this case consider the crossing outlined by the red square. We use the Kauffman crossing rule (first line of Fig. 3) to replace the red box on the left with the sum of the two red boxes on right, with appropriate coefficients of A and A^{-1}. The rest of the knot stays unchanged. So now we have a sum of two pictures of knots with coefficients. In each of these two pictures, we still have crossings, which we have outlined in the blue dotted boxes, so we must apply the crossing rule again to each of these blue dotted boxes, resulting in the four diagrams (and corresponding coefficients) on the second line of Fig. 4. At this point, none of the diagrams have any crossings, so we can apply the second Kauffman rule from Fig. 3 – each loop gets a value of d (i.e., a diagram with two loops will get a value of d^2, and so forth). This leaves us with the purely algebraic expression on the third line on Fig. 4. With a little bit of algebra (and recalling the definition of $d = -A^2 - A^{-2}$) we obtain the final result, which is just 'd'.

Fig. 4: Evaluating the Kauffman invariant of a very simple knot.



made it look extremely complicated, and still the value of the Kauffmann invariant would be just 'd'[3].

So let us now return to the knots in Fig. 1. One can follow the same procedure to evaluate the Kauffman invariant of the knot on the left, which (without going through the details) turns out to be A^6, and the Kauffman invariant of the knot on the right turns out to be $A^7 (1 + A + A^2 - A^4)$. Since these two expressions are not equal to each other, we know immediately that there is no way the two knots can be deformed into each other without cutting the strands.

COMPLICATED KNOTS

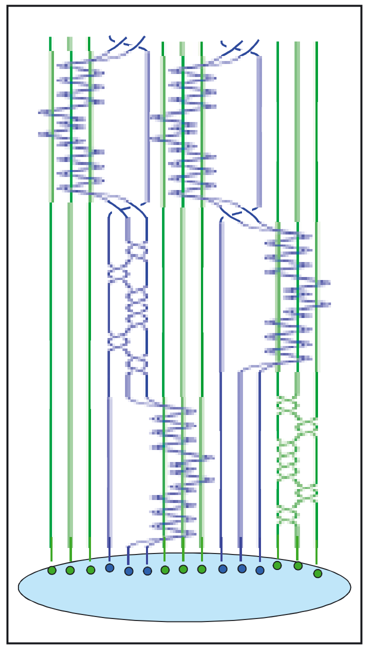
Now suppose one is given a very complicated knot with many over- and under-crossings. To figure out what this knot is equivalent to, one might be tempted to follow the above described algorithm to evaluate the Kauffman invariant. Unfortunately, for complicated knots, the Kauffman invariant turns out to be exponentially hard to evaluate. To see this, simply note that when we followed the Kauffman algorithm, each crossing of strings doubled the number of diagrams we had to consider. In the example of Fig. 4, there were two string crossings, and we ended up with four diagrams. If there had been three crossings we would have eight diagrams, and so forth. It is very easy to make a complicated knot with 100 crossings: evaluating the Kauffman invariant of such a knot would require keeping track of 2^{100} diagrams. This number is so huge that even the world's biggest computer would not be able to do the calculation in a hundred years. This might make one think that the Kauffman invariant is not so useful for distinguishing complicated knots from each other.

However, let us now return to our above discussion of anyons. As mentioned there, the properties of the particles depend on the space-time knots that their word lines have formed. More specifically, the probability that all of the particles re-annihilate at the end of the space-time knot is given by the square of the Kauffman invariant[4] (for some particular value of the constant A). The reason this is interesting is because it suggests a method of determining the Kauffman invariant for complicated knots. If one had anyons in a laboratory, all one would have to do is to move particles around in such a way as to form a desired space-time knot in their world lines. Then by measuring whether the anyons annihilate at the end of the knot (doing the experiment many times to determine the probability of annihilation) one can make an accurate estimate of the Kauffman invariant – something that, as mentioned above, the world's largest computer would never be able to do, even in a hundred years. We conclude that these anyons have a calculational ability that modern computers do not have!

Now one may not be particularly interested in evaluating the Kauffman invariants of complicated knots. But it turns out that this anyon computer has the same computational ability as other quantum computers. Any quantum computation can be turned into a knot, and the end result of the computation is determined by observing whether particles re-annihilate or not. The idea of building a quantum computing device using anyons is an approach known as topological quantum computation[5].

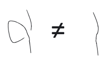
Let us now return to the key challenge of quantum computation – errors from small amounts of noise in the environment. Let us think about how noise might effect a topological quantum computation. To perform the computation we must move the anyons around each other so as to form certain space-time knots. Noise impingent upon an anyon will shake it around. However, as long as it is not shaken so much that the knot is changed to a different knot (so that we have an inequivalent knot to the one we intend) the final knot formed by the anyons remains the same, and the computation remains unchanged. In other words, the topological quantum computer is inherently immune to small amounts of noise!

The physics of anyons remains to be explored in detailed experiment. Despite the fact that the field is in its experimental infancy, the inherent immunity to noise makes it still considered to be one of the most promising approaches towards building a quantum computer[6]. Indeed, the Microsoft corporation has invested heavily in this approach and has built an entire research centre devoted to pursuing the topological approach to quantum computation. Other researchers around the world (like myself) are also very interested in pursuing this approach and have devoted their research careers to exploring the physics of anyons. Whether or not this approach will be the one that finally enables the world to build a quantum computer, one thing is certain – the physics of anyons will be an exciting research field far into the future. ■



Above: This knot corresponds to a simple circuit for a quantum computer.

3 One should be careful in declaring two knots equivalent to each other. For example, the following two pieces of knots are, in fact, inequivalent.



While it appears that these two pieces of knots can be deformed into each other without cutting, more careful inspection shows that pulling the string on the left tight results in a twisted string, as shown more clearly here by thickening the strings into fat strings like ribbons.

Anyone who has ever tried to straighten a garden hose will understand this immediately.

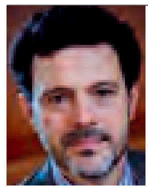
4 There is a normalisation factor as well, which I am brushing under the rug.

5 While many people have been involved in developing the idea of topological quantum computation, the original idea is usually credited to Michael Freedman (another Fields medalist) and Alexei Kitaev, one of the inaugural 'Fundamental Physics' prize winners (worth a whopping three million dollars!)

6 At a technical and mathematical level the ideas of topological quantum computing are very closely connected to the ideas of error correcting quantum codes – something Andrew Steane is quite famous for (although his introductory article in this newsletter barely touches on the issue!)

'QUANTUM MATERIALS'

Exotic material properties from strong quantum mechanical correlations



Prof Paolo Radaelli

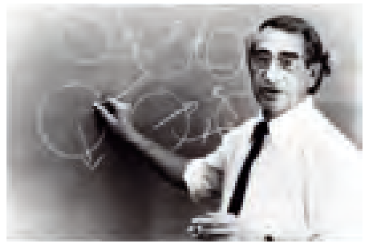
A REMARKABLE THESIS

In 1928, Swiss physicist Felix Bloch obtained his PhD at University of Leipzig, under the supervision of Werner Heisenberg. In his doctoral dissertation, he presented what we now call the quantum theory of crystals, and what a momentous occasion that was: much of the technology around us – from digital photography to information processing and storage, lighting, communication, medical imaging and much more – is underpinned by our understanding of the behaviour of electrons in metals (like copper) and semiconductors (like silicon). In essence, Bloch postulated that the most important properties of these materials could be calculated by assuming that the conduction electrons act almost independently from each other, as though they were gliding serenely in a landscape defined by the electrostatic potential of the atomic nuclei and by the 'core' electrons. The consequence is that electrons are only allowed to have energies within certain 'bands', while other values of energy are forbidden. The band structure of metals and semiconductors is still at the core of our Condensed Matter Physics undergraduate teaching today.

Sir Nevill Mott (1905–1996) was awarded the Nobel Prize for Physics in 1977 together with Philip Warren Anderson and John Hasbrouck van Vleck 'for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems'.

CROWD CONTROL

The success of Bloch's theory is all the more remarkable when one considers how unlikely it appears to be. At first sight, electrons in solids should by no means be independent: the electrostatic force between electrons at atomic distances is huge, and nothing permits us to think that it can be ignored altogether. So, how come Bloch's theory works so well? Many great physicists, including Enrico Fermi and Jens Lindhard, provided key insight, but soviet physicist Lev Landau finally solved the puzzle. He understood that, indeed, most electrons do not behave independently, but they are trapped deep inside the Fermi sea – the set of occupied states in a metal – and do not contribute to the low-energy properties relevant for many of the most interesting experimental probes. Only electrons 'at the edge of the crowd' (i.e., at the Fermi surface) are important, and those electrons can be considered as almost independent, provided we make a correction to their masses.



John Hubbard (1931–1980), explaining on the blackboard the connection between electron correlations and magnetism.

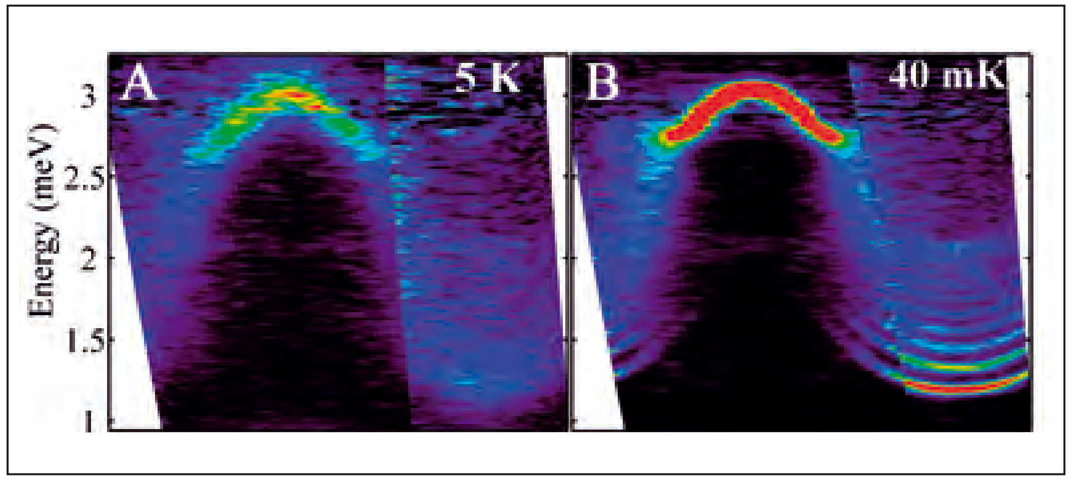
ODD ONES OUT

Although band structure theory has proven to be extremely effective, it does eventually break down. In some cases it leads to completely wrong predictions even on the most fundamental issue of whether a material should be a metal or an insulator. Materials of this kind are known as 'Correlated Electron Systems' (CES). As metals and semiconductors go, CES are very odd: most do not look like metals at all, many are rather similar to rust – in fact, the first CES to be studied, beginning in the 1930s, is Fe_3O_4, quite literally, black rust. Most CES have also very strange magnetic properties, quite different from those of ordinary magnets such as iron. Electron correlations and magnetism are deeply intertwined, as first demonstrated by the pioneering work of two British theoretical physicists, Sir Nevill Mott (1905–1996) and John Hubbard (1931–1980). CES can have other remarkable properties, with many prospects for applications that can profoundly transform our technology. Take for instance superconductors – materials that lose their electrical resistance completely when cooled below a certain temperature (known as T_c.). Superconductivity is already a core technology in medical imaging (MRI scanners) and is a key component of future fusion reactors such as ITER. With materials improvements, superconductors could revolutionise communications, energy distribution and transportation, and even lead to the construction of a viable quantum computer.

Ordinary metals are not very good superconductors – the best need to be cooled below 23.2K (-250ºC). This record, set in 1973 by the Nb_3Ge alloy, was smashed 13 years later by $LaBaCuO_4$, a type of CES, with a T_c of 35K, a discovery that earned Georg Bednorz and Alex Muller the Nobel Prize in 1986. Very quickly, other copper oxides were found with even higher T_c, the current record standing at 133K.

MAGNETIC PERSONALITIES

To date, no universally accepted theory of high-T_c superconductivity has been developed. However, most physicists think that the strange magnetic properties of copper oxides are an essential ingredient to reach such high temperatures. Very recently, a new class of high-T_c superconductors, based on iron rather than copper, has been discovered, where magnetism is believed to play a key role. Meanwhile, many other CES properties have been studied: the electrical resistivity of some CES materials can be changed by several orders of magnitude by applying a magnetic field – a phenomenon known as Colossal Magnetoresistance. Other CES, called multiferroics, combine two properties so far employed separately in information storage: ferroelectricity (as found in chip-and-pin cards) and magnetism (as in hard disks). Beyond blue-sky research, a major international research effort is directed at developing 'CES electronics', which might complement or even replace silicon in the future.



Left: 'LHC in a bottle': one of the most curious aspects of magnetic phenomena arising from strong correlations is that they can often be described in the language of high-energy physics. For example, magnetic excitations in the quantum magnet $CoNb_2O_6$ consist of 'kinks' carrying fractional spin quantum number, analogous to quarks. This leads to a continuum of scattering in the inelastic magnetic neutron scattering cross section, see panel A. At lower temperatures, spontaneous symmetry breaking leads to the confinement of kinks into a series of 'meson-like' bound states, giving rise to narrow dispersing peaks in the neutron scattering cross section (panel B).

CLARENDON CORRELATIONS

The Quantum Materials group in the Clarendon Laboratory has a thriving programme of research on CES and their applications. The roots of this interest can be traced back to the pre-WWII era, when Nicholas Kurti, Kurt Mendelssohn and Franz Simon built in Oxford one of the most advanced low-temperature laboratories in the country. In the fifties, the best high-field superconducting magnets – essential for the study of CES – were being built in the Clarendon – an activity that inspired Martin Wood to create Oxford Instruments out of his garden shed in Northmoor Road. A key asset of the Clarendon Laboratory in this field is the proximity to the Rutherford Appleton Laboratory, since the ISIS neutron source and the Diamond Light source provide unique tools for CES studies. Today, in the Clarendon, we grow perfect crystals and perfect films (in essence, two-dimensional crystals grown on top of a single-crystal template) of a variety of CES, including novel superconductors, multiferroics and even more exotic systems with unique quantum properties. Their magnetic and electronic properties are studied at temperatures down to 0.05 K and in magnetic fields up to 65 Tesla – a UK record. We gain further insight by bombarding these crystals with X-rays, neutrons and even exotic muons at national and international facilities, which enables us to see how properties evolve at an atomic level. On the applied side, the Clarendon Laboratory is collaborating with UK industries active in medical imaging and cryogenic instrumentation, and has recently become part of a new Centre for Applied Superconductivity, a £6.5M joint venture funded through the Oxfordshire Local Enterprise Partnership. One of the missions of the Centre is to develop new materials, including CES superconductors, to be deployed in a wide range of technologies. ■

PICTURE COURTESY OF CREATEC FISCHER & CO. GMBH

Left: A new tool for thin film quantum materials research. Developed jointly between the Quantum Materials group and Createc GmbH (Erligheim, Germany), and installed on the high-resolution ARPES beamline I05 at the Diamond Light Source, the miniMBE allows us to explore novel oxide thin films. Molecular beam epitaxy, or MBE in short, is uniquely suited for synthesizing novel materials with the highest possible purity, one atomic layer at a time. The growth of the single-crystalline layers is monitored *in situ* with electron diffraction, allowing for a precise control of the growth process. MBE is key for modern quantum materials such as quantum well structure, but also being used for practical applications such as lasers, electronics, solar cells, and radars.

MOSELEY AND X-RAYS

Prof Derek Stacey, Emeritus Professor, Atomic and Laser Physics

Henry Gwyn Jeffreys Moseley fell in Gallipoli 100 years ago. In this, the last of three articles commemorating his life and work, Derek Stacey reflects on how Oxford Physics has changed since Moseley's time.

© ROBIN MARSHALL

Robert Clifton. The only research of any note undertaken in the Clarendon during the 50 years he was in charge was the redetermination of the universal constant of gravitation, carried out in the cellars by C. V. Boys of the Royal College of Science in London.

John Townsend. Appointed in 1900, he was not given space in the Clarendon by Clifton and had to wait until 1910 to get his own Laboratory.

MOSELEY'S OXFORD

In 1906, the year Moseley came up, Oxford Physics was in a dire state. Educational reforms in the previous century had forced the university reluctantly to establish an Honours School in Natural Science, but the general view was still that the study of the ancient world was the only basis for a sound education. One don commented 'The attempt to foist physical researches on Oxford…is a sheer waste of labour and money. All this is only to distract and enfeeble the task of serious education...' Another referred to 'a dirty little First in Nat. Phys. or whatever it is.' 75 of the Scholarships offered by Oxford in 1906 were reserved for classicists, only 14 for scientists.

Nevertheless, even in this discouraging environment it would doubtless have been possible for a forceful and dynamic leader to establish a vigorous and successful physics department. Unfortunately, the Professor of Experimental Natural Philosophy, Robert Clifton, was not of this ilk. By 1906 he had been in charge for more than four decades, but he had built up no research base and had published nothing himself for some thirty years. John Townsend, appointed in 1900 as Wykeham Professor, carried out some notable research on gas discharges, but the exciting developments which were changing physics forever were of no more interest to him than they were to Clifton.

Moseley, then, was to breathe life into this corpse in 1914 with his ground-breaking work on X-rays, as I have already described. However, his first experience of the university was as an undergraduate at Trinity. The first hurdle for scientists was Responsions, an entrance test for which knowledge of Latin and Greek was essential. Moseley was excused this on the basis of his record at school, where he had won prizes for classics. Honour Moderations were taken at the end of the first year; they consisted of a compulsory paper on Holy Scripture and another on either mathematics or (inevitably) ancient languages. The mathematics echoed this theme, as it included the first four books of Euclid; there was no calculus, presumably because the Greeks did not invent it. One could thus proceed through to the second year without any evidence at all that one had progressed in physics. The syllabus for Finals, taken by Moseley in 1910 after four years of study, was purely on classical physics. One might say that such recent topics as relativity, X-rays, the electron and the photoelectric effect were omitted because they were not yet sufficiently understood; but in truth the academic staff were not remotely interested in understanding them. Even the electromagnetic theory of light, which dated back nearly fifty years, was not examined.

So how did Moseley get on in this environment? His studies were overseen by a chemist, D. H. Nagel, as Trinity had no physics tutor. This was probably the best he could have hoped for. According to his obituary in *Nature*, Nagel 'did much to remove the prejudice keenly felt in Oxford [against science]… and the University has lost a teacher remarkable for the thoroughness, the understanding and the sympathy which endeared him to many generations of undergraduates.' Trinity arranged for a physicist at St. John's to tutor Moseley. According to an early termly report he was 'good but flighty.' It will come as no surprise that Moseley preferred to be left to his own devices. He would work away at some project with an eye to presenting it at one of the scientific societies of which he was an active member, the Alembic Club or the Junior Scientific. Remarkably, his 'flighty' topics included a model of Wilson's cloud chamber, and a paper on electronic theories and the spectrum. These of course were of no help to him whatsoever in Finals, in which he gained a second-class degree, despite a prodigious effort in the run-up (when he was described as 'improving in definiteness; able and industrious'). To put this in context, one First in the entire university was awarded in physics that year, and indeed Moseley was only the second Trinity undergraduate ever to have sought Honours in the subject. Moseley, later described by his contemporary, Charles Darwin, as 'without exception or exaggeration the most brilliant man' he had ever met, did not, alas, know enough about such weighty matters as the fringe location in the Jamin refractometer to pass muster.

THE GROWTH OF RESEARCH

With Moseley killed in action, Clifton's successor, Frederick Lindemann, took up the challenge of raising the profile of Oxford physics after the war. He had two problems: the deep-seated hostility within the University to the growth of science (he was famously told 'anyone with a First in Greats can get up science in a fortnight') and the attractiveness to promising researchers of vigorous groups elsewhere, notably the Cavendish in Cambridge, where Rutherford was now in charge. Lindemann's opportunity came in the early 30's when he recruited high-calibre physicists whose careers in Germany were threatened by the anti-Semitism of the Nazis. Under his direction the Department's reputation started to flourish in the areas of atmospheric physics, low-temperature physics and spectroscopy; even so, in 1939, when Physics moved into the present Clarendon Laboratory, there were still only six physicists with college Fellowships in the whole university. The big breakthrough came after the war. A young St. John's man, Brebis Bleaney, realised that the microwave technology he had been working on for radar in the war effort could be applied to fundamental problems and built up a large and highly productive research effort. Bleaney became Dr Lee's Professor in 1957, and in the same year Denys Wilkinson arrived in Oxford to start a major programme in nuclear physics. Under Bleaney, the Department became one of the largest in Europe. 'Spin-off' companies took advantage of the technology developed in the Clarendon. Crucially, the Department gradually became less parochial; researchers and graduate students alike now come to Oxford from all over the world.

Inevitably, the nature of research has changed over the years. Two photographs of Moseley's apparatus were shown in the last newsletter; they were fine examples of the string and sealing wax school of experimental physics. Then, and for many years after, it was possible to carry out significant work with a good glass-blower, a modest budget and enough ingenuity. Of course, there are still striking examples of advances made without expensive equipment, but they are very much the exception. Not so long ago, it was a major achievement to observe a single atomic ion held in space in a simple electromagnetic trap; but present-day research aimed at using such an ion as an element of a quantum computer requires stabilized lasers and a microfabricated trap in an ultra-high vacuum, all in a vibration-free air-conditioned and temperature-stabilized laboratory. Such work demands substantial funding and a team of researchers covering all the required areas of expertise. As many articles in these newsletters have demonstrated, Oxford has thrived under these conditions, carrying out front-line research in areas as diverse as particle physics, superconductivity and the physics of biological systems. The Chairman is fond of saying that we can aspire to be among the best in the world; our success in attracting funding, and (more importantly) the use of it to produce exciting and novel results, suggest that it is not an unreasonable aspiration.

With an increasingly crowded syllabus, we must take care that the joy of enlightenment through discussion does not get lost in the race to get through the material.

TUTORIALS THEN AND NOW

Much has changed in our teaching practice since Moseley's time. There is now an overall scheme of lectures, presenting the syllabus in a systematic way at a level appropriate to the examination. Students are trained in public speaking. The four-year course involves specialist departmental classes, and a substantial amount of open-ended project work. At the heart of it all, though, is still the tutorial. Moseley will have turned up each week with an essay, the reading and discussion of which occupied the hour. I was taught this way myself in the 1950's. Present practice varies from college to college, but Moseley's *alma mater*, Trinity, is typical: there are around half-a-dozen physics students per year, taught mainly in pairs by two Fellows of the college. The essay has been replaced by the setting of problems, often devised by the lecturer; the students' efforts are scrutinized in advance by the tutors, and form the basis for tutorial discussion.

Does this represent an improvement? One could argue that it is more efficient. A tutorial is likely to be more illuminating if the tutor knows beforehand what a student's misconceptions are, and to be able to produce a well-constructed essay does not guarantee that one is able to solve problems. But there are dangers. Producing a solution to a problem does not guarantee that one has understood the underlying physics. The reason a tutorial is so valuable is that the tutor can bring the student to an understanding of conceptual material by adroit questioning and argument. The aim is that eventually the students should learn to ask the questions for themselves. This is the skill we are trying to pass on; but it all takes time, far longer than simply pointing out where a student has gone wrong and moving on to the next problem. With an increasingly crowded syllabus, we must take care that the joy of enlightenment through discussion does not get lost in the race to get through the material.

We need also to take into account the very different social mix we now have in Oxford. It was taken for granted at Eton in Moseley's time that the purpose of an education was to prepare young men of good family for the privileged positions they would occupy in society and the British Empire. (This of course included willing self-sacrifice in the service of one's country; Alexandra Churchill[1] says that Moseley 'not only displayed a relentless determination to…put himself in harm's way, but…refused numerous job offers connected with the war effort that did not require getting shot at.') The best were sent to Oxbridge, along with those from the other great public schools. We could therefore count on expert preparation (mainly in classics, naturally) for the courses they would follow.

Things are very different now; students come from a wide variety of backgrounds, and the University is immeasurably the richer for it. It was, I think, once true that Oxford felt some obligation to give an education to those who would lead the country, however stupid they were. However, I have been involved in admissions now for fifty years and have seen no evidence of anything other than a desire to take the most able candidates. Over the years, thanks to departmental and college open days, and our many outreach activities, we have been increasingly successful in attracting applicants from schools of all types. Inevitably, though, this has led to a wide variation in the level of preparedness for a university course. Some students have no experience in problem-solving; those who are not used to discussion sessions can find tutorials bewildering. It is up to us to continually re-examine our teaching methods to keep them effective with a changing clientele. Moseley could manage very well on his own, but after all he was in a class by himself. ■

It is a pleasure to thank Prof Justin Wark and the Archivist at Trinity, Clare Hopkins, for much valuable background, including access to the records of Moseley's progress. I am grateful to them, to John Heilbron and to Liz Bruton for comments on the manuscript. John Heilbron's book, H. G. J. Moseley, *University of California Press 1974, has been as ever a mine of information.*

1 in *Blood and Thunder*, The History Press 2014

I have been involved in admissions now for fifty years and have seen no evidence of anything other than a desire to take the most able candidates. Over the years, thanks to departmental and college open days, and our many outreach activities, we have been increasingly successful in attracting applicants from schools of all types.

Frederick Lindemann. Francis Simon, Kurt Mendelssohn, Heinrich Kuhn and Nicholas Kurti were among the scientists he recruited, saving them from Nazi persecution. Mendelssohn wrote[1]: 'When Lindemann became professor at Oxford, the Clarendon Laboratory resembled inside and out a stage decoration for Göethe's *Faust*. When he retired, it had become one of the largest and most flourishing physics departments in the world.'

1 in *The World of Walter Nernst*, Macmillan 1973

Brebis Bleaney. He took advantage of the low temperature techniques and high magnetic fields in use in the Clarendon to develop the new field of electron spin resonance. His name will be familiar to many alumni from his textbook *Electricity and Magnetism* (OUP), which he co-wrote with Betty, his wife.

The original Clarendon Laboratory, designed by Clifton and built in 1872. Even in Moseley's time, the building was not wired for electricity. The present Clarendon was completed in 1939. Now, 100 years after Moseley's death, a new era begins as work gets under way on the Adrian Beecroft Building, a state-of-the-art laboratory suited to modern research needs.

THE HENRY MOSELEY SOCIETY (HMS)

Honouring the past, building the future

By becoming a member of the HMS, alumni and friends of the Department can contribute to the next great breakthroughs made by Oxford Physicists. There are a number of benefits associated with becoming a member and you can find out more about it here or by getting in touch with Val Crowder: alumni@physics.ox.ac.uk

NOTES FROM THE HEAD OF PHYSICS

Prof John Wheater, Head of Department

It has been an excellent few months for Oxford Physics. We have been awarded the largest ever single research grant received by the Department, did as well as we could possibly have hoped in the government's regular assessment of the research of university departments, and have made major progress towards the construction of the new building.

QUANTUM INFORMATION SCIENCE

Research into quantum information science in its modern form began in the Clarendon Laboratory in Oxford in the late 1980s when Artur Ekert, David Deutsch and collaborators started to develop the theoretical underpinnings of the subject. They developed the basic ideas of quantum cryptography and quantum computing and over the years a number of further seminal developments in the subject were made in Oxford, for example Andrew Steane's work on quantum error correction. During the same period the technological capability to manipulate individual quanta grew rapidly with the development of more sophisticated lasers and of new sensors able to detect very small amounts of energy reliably. This led to the establishment of experimental groups working on the physical implementation of qubits, the basic element holding one bit of quantum information, and on photonics – the business of manipulating quanta of light. These efforts have prospered and today the Ion Trap Group led by David Lucas has built devices implementing one- and two-qubit operations with world-leading performance far in excess of that required for a quantum computer.

With this strength in the basic quantum science we were in a strong position when the UK National Quantum Technology Programme to develop laboratory level systems into technology demonstrators was announced by the government in late 2013. We were delighted when the award of £38M over five years to the resulting Networked Quantum Information Technologies (NQIT) programme was announced in November 2014. NQIT is led by Oxford Physics under the Directorship of Ian Walmsley and also includes scientists from the departments of Computer Science, Engineering and Materials, eight other universities and a number of industrial partners. NQIT's core mission is to develop the Q20:20 quantum engine, an optically-linked network of 20 cells, each cell being a quantum processor with 20 matter qubits; success would be a big step in demonstrating the technological viability of quantum computers.

RESEARCH EXCELLENCE FRAMEWORK

Every six years the High Education Funding Councils for England and Wales, the Scottish Funding Council and the Department for Employment and Learning in Northern Ireland conduct an exercise, the Research Excellence Framework (REF for short) to determine the standing of research conducted by UK university departments. The outcome of this exercise determines the apportionment of the government block grant for research for the following six year period. In December 2014 we learned the outcome of REF 2014. Oxford Physics did extremely well.

Below: plans for the new building

We were judged overall to have the highest proportion of 4* (equals world leading) research of any UK physics department. We had the highest proportion by a considerable margin, and the highest absolute number of 4* rated research papers of any UK physics department; by absolute number Cambridge came some way below us despite having 20% more staff, and the third-placed institution, Imperial, had only two-thirds our number of 4* papers. Oxford and Cambridge were judged to have the joint best research environment (measured by a complicated cocktail of data and more subjective judgements), with Imperial, Edinburgh and St Andrews a distant 2nd. This is a seriously tough target to live up to in 2020!

Mr Adrian Beecroft

Above: Artist's impression of the Beecroft Building seen from the University Parks.

HEARTFELT THANKS

This issue contains the last article in Derek Stacey's series on Henry Moseley, Oxford's first world-class physicist. I hope you can see that his legacy is thriving but, as I have written before, to keep all this going into the future it is imperative that we replace our super-annuated infrastructure. In January many of you received an email from me asking for your support to help us reach the £8m fundraising target for the new building, now named the Beecroft Building in acknowledgement of Adrian Beecroft's generous gift, before the due date of 31st January 2015. The response was astonishing and gratifying. Over a few short weeks more than £0.5m was pledged, the membership of the Moseley Society – for donors who give more than £1,000 – rose to over 60, and we reached the target with a few days to spare. As I write, the paperwork to release funds for construction is working its way through to the University Council and notices warning of imminent closure have been posted on the car park; by the time you read this, and if all goes smoothly, it will have been dug up for the last time! To all of you who have contributed, our heartfelt thanks. It is not too late to help. Every donation reduces by twice that amount the capital deemed to be borrowed by the Department from the Capital Fund, and thus the servicing charge we have to pay, so that the total benefit to the Department over the lifetime of the building is about four times your gift. ■

Right: Artist's impression of the Beecroft Building seen from the corner of Museum Road and Parks Road.

MAKE A DIFFERENCE

Connect – Collaborate – Contribute

There are many ways in which you can contribute to the Department. You could volunteer time, ideas, or contacts; offer placements for current students in your workplace; or donate monetary gifts, which are invaluable to our work. Visit www.physics.ox.ac.uk/alumni to find out more.

FORTHCOMING ALUMNI EVENTS

The Department offers a series of special lectures, events and other opportunities to engage and keep connected. The most up to date information and details can be found on the website at www.physics.ox.ac.uk/events.

PHYSICS ALUMNI LECTURE AND RECEPTION

8 May: Museum of the Soldiers of Oxfordshire (6–8:30pm). In 2015 we will be celebrating and honouring the life of physicist and alumnus Henry Moseley, who made incredible achievements for science during his time in Oxford, before going to WWI. The new museum 'Soldiers of Oxfordshire' in the beautiful location of Woodstock will be our venue for this alumni event, which will include talks, a tour of the museum's special exhibition and collections, followed by drinks and canapés.

SATURDAY MORNING OF THEORETICAL PHYSICS

Members of the Rudolf Peierls Centre for Theoretical Physics host a 'Saturday Morning of Theoretical Physics' several times a year. The next event 'From quantum bits to exotic particles' is on **9 May** and focusses on various aspects of quantum computation.

THE HENRY MOSELEY SOCIETY INAUGURAL EVENT

19 May: Oxford Museum of the History of Science and Trinity College (6–10pm). This is an event for Henry Moseley Society members only. If you would like to know more about this event, or learn about how you could become a member, please email us.

ALUMNI GARDEN PARTY (INCORPORATING ATOMIC & LASER AND CONDENSED MATTER PHYSICS ALUMNI EVENT)

27 June: Save the date! Due to building work around the Clarendon Laboratory, the 2015 Garden Party and AL&CM Alumni event will be held at St Annes. It promises to be a fantastic occasion for the entire family to enjoy.

If you are interested in any of these events, please register on our website: www.physics.ox.ac.uk/events, or contact the alumni office: alumni@physics.ox.ac.uk.

OXFORD LEADS HUB FOR NETWORKED QUANTUM INFORMATION TECHNOLOGIES

Dr Joshua Nunn

In December 2013 the UK quantum information processing community was galvanised by the announcement from George Osborne that the Treasury would be investing £270M in quantum technologies – the result of effective and thoughtful lobbying, not least from our own Pro-Vice-Chancellor for Research. After a fraught 2014 preparing proposals, forging collaborations and making approaches to a surprisingly responsive industrial sector, we have finally received the official award letter establishing Oxford as the lead partner of the Hub for Networked Quantum Information Technologies (NQIT) www.nqit.ox.ac.uk.

EPSRC has established four such Hubs, with the other lead institutions being the universities at Birmingham, Glasgow and York. Crudely, the focus areas of these Hubs are in quantum sensing, quantum imaging and quantum communications. The Oxford-led Hub completes this picture by focussing on – yes, the craziest possibility – quantum computing. NQIT will take the bull by the horns and deliver a platform for scalable quantum computing. We hope, no – we are confident! – that the science will work; it's quite thrilling to be given the funds to chase this dream to ground.

With a total budget of £38M over five years, NQIT is a collaboration of nine universities: Oxford, Sussex, Southampton, Edinburgh, Strathclyde, Bath, Cambridge, Leeds and Warwick. More importantly though, for a project aimed ultimately at bringing products to market, are our industrial and commercial partners: 20 forward-looking companies with interests ranging from supplying the research community with bespoke laboratory tools to acquiring the intellectual property for disruptive innovations. You will have heard of the bigger ones: Google, Lockheed-Martin… But what is perhaps most encouraging is the widespread interest from smaller UK SMEs, who committed cash and expertise to secure the success of the project.

And the quantum computer? We are adopting a hybrid 'light-matter' approach, where the hyperfine spin states of trapped calcium ions provide registers of several quantum bits (qubits), which are then coupled optically by interfering fluorescence from ions in adjacent traps. A network of entangled ions is built up sequentially, forming a surface code, which enables quantum error correction. The stated aim of NQIT is to build the Q20:20 engine: a network of 20 traps, each loaded with 20 ions. The goal was chosen because this scale of device is large enough to encode a single, fully error-corrected, logical qubit, which is entirely protected from decoherence (we've nick-named it the immortal qubit!). So, the output of NQIT will be the building block for an arbitrarily large quantum computer. In five years' time we hope to find a manufacturing partner and fill a warehouse with these building blocks. This, like its 20th century warehouse-filling predecessors Colossus and ENIAC, will be the first of a new breed: a computer unlike any before it. And we will have to decide whether its name should be an earnest classical reference, or a whimsical acronym. Or perhaps it will choose its own name. ■

NQIT

The Mathematical Physical and Life Sciences (MPLS) Divisional Board has accepted the recommendation that **PROFESSOR JOHN WHEATER** be re-appointed as Head of Department for a further term from 1 September 2015 until 31 August 2018.

STARGAZING

More than 700 visitors came to the Stargazing event in January and more than 500 in March, showing how much interest there is from the general public in science and astronomy.

Visitors had a chance to find out more about our night sky, from new planets to far-off galaxies and the vastness of the universe. Visitors also learned about how weather in space affects us on earth, what is involved in space exploration, and the wonders of the Milky Way and other galaxies.

The planetarium is always a highlight, and this year the exoplanet weather forecasting and the 'pin the lander on the comet' were both extremely popular activities. Chris Lintott's talk on Beagle 2 drew a capacity audience, as did Colin Wilson's talk about the Rosetta mission of the European Space Agency.

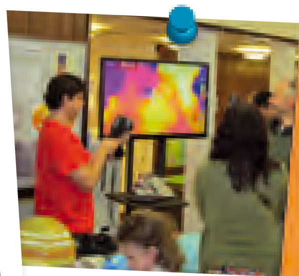
On Friday 20 March the Astrophysics team drew a big crowd outside the SAID Business School for the total eclipse. Members of the Department set up telescopes and guided the general public through the amazing phenomenon.

Keep an eye on all the public events we run: www.physics.ox.ac.uk/events

You melted my brain with space wowness!! Excellent show. Thank you!

Very interesting! Especially happy with the particle zoo & Kathryn's patient explanations

Great event! Loved the astro crafts, 15-min lectures and the planetarium! Children (9+6) very enthusiastic



Shooting at the comet with a Nerf gun. By Izzy 8

I liked the weather forecasting room!

Brilliant – loved the planetarium and the physics equipment

ALUMNI LECTURE AND RECEPTION AT OXFORD AND CAMBRIDGE CLUB

More than 80 alumni gathered at the beautiful Oxford and Cambridge club in Pall Mall, London on 13 March, to hear Prof John Wheater's lecture entitled 'What is Quantum Gravity?'. The topic generated many interesting conversations during the drinks and canapés reception that followed. Alumni from the last seven decades attended, representing a wide range of professions and interests, and making it a night to remember.

PHYSICS COLLOQUIUM SERIES

The Physics Department runs a termly Colloquium series, held on Friday afternoons and open to all members of the University. Alumni are most welcome to attend; it is a great opportunity to visit the Department and meet current and retired members of staff. If you would like to know more about it, please email contact@physics.ox.ac.uk.

CHRISTMAS CAROLS

Jim Williamson (AOPP, Emeritus) has been organising this wonderful event for the past 30 years or so. It is held at St Mary the Virgin Church (High Street, Oxford) usually in the third week in December. Save the date for 2015!

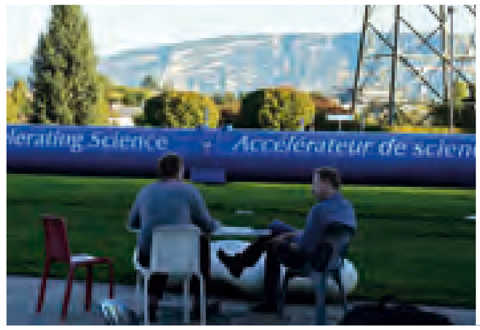
HENRY MOSELEY SOCIETY MEMBERS ENJOY A SPECIAL VISIT TO CERN

The inaugural Henry Moseley Society event will take place on19 May in Oxford. More details at **www.physics.ox.ac.uk/events.**

The first Henry Moseley Society Special Event took place in October, with a visit to CERN, guided by the Head of Department Prof John Wheater, Head of Particle Physics Prof Ian Shipsey, Prof Tony Weidberg, Prof Daniela Bortoletto, Prof Alan Barr, Prof Neville Harnew, Prof Guy Wilkinson and Oxford Physics students who are working on the experiments and based currently at CERN: Kathrin Becker, Oliver Lupton, William Fawcett, William Kalderon, JIahang Zhong, Koichi Nagai, Lydia Beresford and Shu-Faye Cheung.

During the visit, guests enjoyed various lectures, lunch at Restaurant 2, underground visits to ATLAS, LHCb, SM18 and the synchrocyclotron, and time to relax and chat in the lovely setting of Restaurant 1.

In the evening, Dr Peggie Rimmer (Oxford Physics alumna, CERN/CERN Courier and Oxford and Cambridge Dining Club of Geneva) organised a wonderful dinner at the Auberge de Meyrin.



© SUSAN HEZLET

Have you registered as an alumnus/na or friend on our website?

By registering, you will receive advance notice of events and other news, before it is published on the web. There is also a short questionnaire, which will enable us to plan events and services to your liking.

www.physics.ox.ac.uk/alumni/connect

Would you like to host an event for physics alumni?

It could be a drinks reception or dinner, a visit to a special place, to your company, for a small or large group… the possibilities are endless. We may be able to provide financial support and/or assistance, if required, but private sponsorship is always welcomed. Please get in touch for an informal conversation, we'd love to hear from you!

Do you have a photo from your time in Oxford? A story or anecdote that you would like to share?

The alumni office is looking for contributions of this kind, as we are working towards making the archives more accessible and interactive. Send your contributions, no matter how big or small, to Val Crowder, Alumni Officer: alumni@physics.ox.ac.uk.

PHYSICS CAREERS DAYS

Every year the Department holds two career days to encourage and support research staff and students in their future paths.

The 2015 careers event for **post doctoral research assistants** gave postdocs the opportunity to question a panel about their own career paths.

The **undergraduate** careers event took the form of an exhibition and stands from companies that offer programmes for physics graduates. This year we welcomed Elekta, MathWorks, Metaswitch, Rolls Royce, TeachFirst, Tesella and Winton Capital.

If you or your company/organisation would like to take part in next year's events, or have a programme which may benefit our students, please let us know. Email us at contact@physics.ox.ac.uk.

'FIVE MINUTES WITH'…JULIA YEOMANS, FRS

Professor of Theoretical Physics

Tell us a bit about your background

I went to a Direct Grant girls' school in Manchester, where the education was formal by today's standards. It was unusual for anyone to read physics at university; two out of 100 did in my year. I read physics at Somerville, followed by a DPhil in Theoretical Physics. After two years in the US as a post-doc at Cornell, I was lucky enough to be appointed to a lectureship at the University of Southampton, followed by a fellowship at St Hilda's, Oxford.

Can you explain the work you do?

We are interested in active materials, e.g. cells and microorganisms that continuously create energy. These systems naturally operate out of thermodynamic equilibrium and hence provide a testing ground for theories of non-equilibrium statistical physics. They also have potential as micro-machines creating mechanical work from chemical energy, or as swimming micro-robots carrying payloads along blood vessels or through the soil. In addition, we are working on how fluids behave on micropatterned surfaces: when a hydrophobic surface is patterned with micron-scale roughness, it becomes superhydrophobic. Drops hardly wet the surface, retaining an almost spherical shape, and roll off with negligible friction. Nature exploits this surface patterning in many plants, such as the lotus, nasturtium and lady's mantle, to help to keep the plants dry and clean. Tiny ratchets on butterfly wings direct raindrops away from the insect's body, and water striders dance on superhydrophobic feet (see **www.naturesraincoats.com**). With colleagues in Hong Kong, we are looking at new ways drops can bounce on designer superhydrophobic surfaces.

Why do you think it is important to study physics?

Physics teaches problem solving and clarity of thought and is a great training for many jobs. But it is not an easy option and it is important that students are helped over the initial hurdles, not by watering down GCSE and A-levels, but by investing in training inspiring teachers.

What are the most important current challenges in your field?

Science is becoming increasingly interdisciplinary and we are realising that physical approaches using both imaging and modeling are useful ways to think about problems beyond those traditionally defined as physics. We need to break down traditional departmental boundaries so that physicists, chemists and biologists can work together effectively to tackle big issues of health, clean energy and designing novel smart materials.

Can you describe your day to day routine at Oxford?

Every day is different, which is one of the perks of the job. If I can, I prefer to work at home for two or three hours first thing as this gives me time to think and get things done. Then I cycle in to the Department to talk to graduate students, post-docs and visitors, give tutorials or lectures, attend meetings, write papers or work on proposals.

Why is Oxford Physics a good place to work/study?

It is a privilege to work at Oxford. Many of our post-docs and graduate students are outstanding and come up with wonderful research ideas. We are an international community. The tutorial system is a rewarding way to teach – students who have struggled with a problem often just need a small extra push in the right direction for all to become clear.

When did you know you wanted to become a physicist?

I always loved maths and problem solving. The choice between maths and physics at university was difficult but I preferred applied to pure maths and luckily jumped the right way.

What other interests do you have besides physics?

Our four daughters; hiking; tango; orienteering.

What scientific breakthrough would you like to see in your lifetime?

Building a designer cell; discovering life on other planets.

What can be done to increase the number of women in physics?

There has been a lot of research on why women do not choose physics, and a lot of effort to address the situation, with some progress, but no breakthrough yet. I am involved in 'Think Physics', a project in the North East that aims to encourage young people, particularly girls, into STEM-related degrees.

At the senior level in academia things are improving: conferences in soft matter and biophysics usually now have enough women participants that gender ceases to be an issue; four babies joined their mums at the recent Soft Matter Gordon Conference. At more hard-line theoretical physics meetings there is still some way to go.

The Athena Swan Awards are helping to raise awareness of unconscious gender bias. Oxford Physics has gained the bronze award and is currently applying for silver. There is a thriving Oxford Women in Physics society aimed at providing peer support, mentoring and friendship. ■

Julia Yeomans

Julia Yeomans and family at the Royal Society

The Yeomans group meeting

ALUMNI STORIES

DR CHARLOTTE WOOLLEY, MPHYS, DPHIL, KEBLE 2001

When I arrived at Keble in 2001, the same discussion was going on in education then as it is now – what can be done to encourage more girls into studying science subjects? I had always loved science subjects at school, and physics was the natural choice for me, but I remember expecting to arrive and be one of the few girls in the year group, and worrying what that would be like. Luckily for me, Keble had selected a group of eight physics freshers that year with a slightly unusual 50:50 gender split. Working closely with that group of friends, as we wrestled with our tutorial papers each week, gave me my first opportunity really to observe how diverse the styles of thinking and problem solving could be even in a small group, and to appreciate the benefit of drawing on each other's skills to nail a hideous problem!

Alongside studying, my university career was complemented by two outside interests – music and dancing. I was by no means the only scientist who sought outlets for their artistic dreams, and in fact it felt like the majority of musicians or dancers I met were physicists, engineers or chemists. I joined many of the university's classical music ensembles, and have particularly fond memories of playing Shostakovich and Mahler in the Sheldonian Theatre with the Oxford University Orchestra, and of touring Europe with the Oxford Millennium Orchestra. I ended up joining the university dance team after a particularly nasty bicycle accident (an all too frequent feature of Oxford life), which left me unable to play the clarinet for a year. On day one of dance practice I was partnered to a tall Aussie guy, Ian Preston… who turned out to be a physicist in my year, was in most of my lectures and somehow I had never met! It's fair to say our dance coaches would often look on in stunned silence as we tried to iron out a particular dance move with questions like 'But what exactly is the angular momentum in this move?' and 'Should my centre of mass be more this way, or that way?' Through music and dance I met and made friends with a lot of people from every subject, both women and men, and of every age. This reinforced for me the importance of diversity in everything that we do, as the richness of that experience was only possible because of diversity.

By the end of my undergraduate course, I was fascinated with the experimental side of physics and particularly lasers. I joined Simon Hooker's research group and spent four happy years of my DPhil in a darkened lab tweaking mirrors and watching for photons. On completion of the DPhil I didn't quite have the yearning to stay in academia which I had expected to have, and so in 2010 I decided to try something different and joined the Defence Science and Technology Laboratory (Dstl), who undertake science and technology (S&T) research on behalf of the Ministry of Defence (MOD). The training that Oxford had given me to think analytically and independently enabled me to step into totally unfamiliar areas of Defence and Security, and I began to tackle their S&T problems. A good physics grounding is key to being agile in moving from project to project and I was lucky enough to get a fantastic secondment to central MOD in London, during which I used my expertise in lasers to give advice to policymakers on the future trends of directed energy weapons. Having developed a taste for London, and all its associated trappings (well maybe not the crammed northern line in the mornings…), my next and current job was out of Dstl and into central MOD to run S&T programmes on nuclear security.

Working in a military environment is unique, and some of its challenges are ones I had already gained experience in learning to overcome. For example, the military tends to be a male-dominated environment with a task-focused approach to work, which has strong parallels with the undergraduate physicists I met at Oxford and learned to work with through welcoming, encouraging and building diversity in a team. Working with the military is not all challenges though – the military tend to be incredibly meritocratic in their outlook, and once you have demonstrated you are able to contribute good ideas and independent views, their support is 100%, with no distinction drawn whether you are a man or a woman.

The point I am trying to make in looking back to my university days and my still early career, is that I have been lucky enough never to have needed to worry about being 'a girl doing physics' as I have found inclusion and diversity wherever I have been. That seems to have worked for me and for my female contemporaries in physics at Keble. Oxford gave us a great start, and a belief that there were no barriers to achieving anything we wanted. So to answer my starting question of 'what can be done to encourage more girls into studying science subjects?' in my opinion it would be always to take the opportunity to be inclusive and diverse, whenever one is given the choice. ■

© CHARLOTTE WOOLLEY

Dance as creative expression

Keble College

I have been lucky enough never to have needed to worry about being 'a girl doing physics' as I have found inclusion and diversity wherever I have been.

© DAVID HAWGOOD

Dr John Hawgood returning from a research expedition to North Africa. The photo was taken by his brother, David Hawgood, also a physics alumnus.

JOHN HAWGOOD, BA, DPHIL, CHRIST CHURCH 1949

During my 2nd year I spent a vacation working at AERE (Atomic Energy Research Establishment) Harwell under Dr Heinz London, trying to get a distillation system airtight.

This so frustrated me I opted for Theoretical Physics for my final year, getting a 2nd class degree in 1952. (A friend, Lord Primrose, who never attended lectures, was one of the last people to get a 4th class degree!).

I spent 1952-53 nominally studying for a DPhil in Theoretical Chemistry at the Mathematical Institute – but actually spending most of my time on dramatics as a stage manager for OUDS. As a result I was banished to Newcastle, which proved a very good move as I met my wife there (we are still together after 57 years).

My thesis was on the 3-body problem, which of course I didn't solve; but I did get my DPhil in 1955. The next years were spent in Prof J.C. Slater's group at MIT, where I came into contact with time-shaving computing – having already learned machine code for EDSAC in Cambridge.

That was significant because as the first Director of Computing at Durham University I introduced time-shaving using an IBM computer in collaboration with Newcastle – exceptionally funded by the government, which normally only favoured British firms' computers.

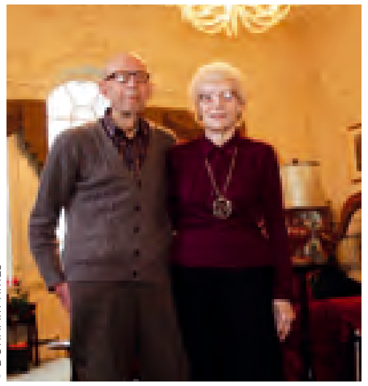
Another vacation job was at Decca Radar, where I made a small but significant contribution to aircraft navigation, using my knowledge of coordinate geometry.

That also came in useful when I used it to design the thermal insulation for early nuclear power plants with spherical shells, for Darlington chemicals.

My interest moved to software system development in several fields over the next 20 or 30 years, including machine translation of Japanese, library automation, university entrance, savings-bank automation and especially participative systems design. In that last field I collaborated with Prof Enid Mumford of MBS (Manchester Business School) and Prof Frank Land of LSE (London School of Economics), also with US and Canadian library researchers.

I became a consultant to both the UK Library Association and the American Library Association after collaborating with Maurice Line, a leaving British librarian, on automation of university, public and national libraries.

Taking early retirement at the age of 50 I spent a year in Brussels on the Esprit collaborative research initiative, then joined PA consulting for further system development projects with EU funding, also MOD projects such as WarGaming. I continued as an MOD committee member and referee for many years after my second retirement, but now I've given up all computing and refuse to use the internet! ■



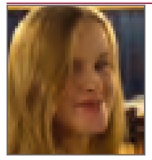
© DURHAM TIMES

Mary and John Hawgood in the stuccoed splendour of their Georgian apartment.

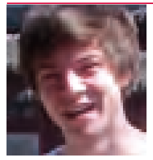
WITH THANKS TO JUDITH CURTHOYS, ARCHIVIST, CHRIST CHURCH COLLEGE

VIRGIN GALACTIC UNITE/GILLIES SCHOLARSHIPS

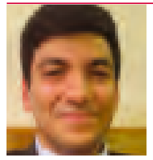
The first recipients of the VGU/Gillies Scholarships tell us about their experience so far, and we welcome this year's awardees



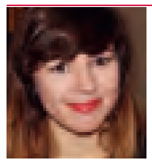
JEMMA BROWN (2014/15) Receiving the Gillie's Scholarship this year has been a fantastic experience. It has given me the opportunity to meet several 'future astronauts' and key people working within Virgin. I have also benefitted hugely from the mentorship of Wade McEldroy, a propulsion engineer. All this has allowed me to see the space industry from a completely new and exciting perspective!



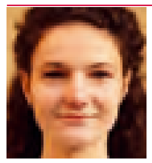
DANIEL MARTIN (2015/16) One of my passions is finding new kinds of communication with younger generations. To that end I run the YouTube channel OxVlog, and I travel to schools internationally to give workshops that lie on the border of mathematics and entertainment with the Oxford-based group 'Marcus's Marvellous Mathemagicians'. I am very grateful to the Oxford physics department for their support.



RAVIN JAIN (2015/16) I'm currently a third year physicist at Merton College. In this year's course we studied a wide range of topics, but the areas of 'complexity' and 'chaos' piqued my interest and I hope to explore them in more depth next year. Outside of physics, if I'm not helping with an outreach initiative, you can most likely find me in a go-kart!



FRANZISKA KIRSCHNER (2014/15) Since receiving the Scholarship, I increased the amount of outreach work I do without having to worry about the costs; I have been able to take up more unpaid opportunities and I'm currently organising a trip to America to hopefully take part in more activities! I've also had the chance to meet with a range of fascinating people from Virgin Galactic and I have been invited to visit Spaceport America – a dream come true!



OLGA ZADVORNA (2015/16) I am a third year undergraduate Physics student from Ukraine. I found my true passion in Particle Physics. My dream is to use it to develop new tools for treatment and diagnosis of deadly diseases such as cancer. I am hoping to do an internship in Medical Physics this summer. All my thoughts, however, are with my family and friends in Ukraine.

© JOHN CAIRNS

Image right: Galactic Unite scholars, L-R: Daniel Martin, Ravin Jain, Jemma Brown, Alberto Chang-Rajii (future astronaut supporting undergraduate bursaries for two STEM students at Oxford), Olga Zadvorna, Stephen Attenborough (Commercial Director for Virgin Galactic), Caroline Sheffield (Content Executive, Virgin Galactic), Franziska Kirschner.

WOMEN IN PHYSICS

Oxford Women in Physics

The Women in Physics Society is going from strength to strength. Since its creation we have hosted a variety of meetings and events, including the now well established monthly coffee meetings and the mentoring programme. For more information, contact Dr Androula Alekou: androula.alekou@physics.ox.ac.uk.

Last November we had a wonderful visit from alumna Jean Chu (St Hugh's), who met with the Oxford Women in Physics group in the Common Room (Clarendon Laboratory) during one of their regular meetings. Also pictured is Prof Derek Stacey. Jean shared some experiences of what it was like to be a female physics student in the late 50's, and reminiscences of her career. You may have read about her in the 'Alumni Stories' section of the Autumn 2014 physics newsletter, available here.

The Physics Department has a presence on Facebook, Twitter, LinkedIn and Instagram. Join the conversation:

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PROFESSOR ROGER COWLEY, FRS (1939–2015)

WITH THANKS TO WADHAM COLLEGE

Roger Cowley, who has died aged 75, was one of the leading physicists of his generation. He was a highly versatile scientist who made important contributions to the understanding of the motion of atoms in solids and liquids, the mechanisms of structural phase transitions, and to a range of magnetic phenomena. Adept at both experiment and theory, he had the rare gift of being able to see through the layers of complexity that often cloud real-world materials and capture the essence of their behaviour in simple models.

Cowley's deep intellect and analytical powers emerged early on. As a research student in Cambridge (1960-1963) he performed neutron scattering experiments to study the atomic vibrations in crystals and developed related theory. In a highly influential experiment he showed that the anomalous dielectric properties of crystals like $SrTiO_3$ are associated with a low-frequency vibration, the so-called 'soft-mode', and in a seminal review he developed a method to calculate anharmonic properties such as thermal expansion and thermal conductivity using Feynman diagrammatic perturbation theory. Cowley published ten papers from his PhD work, seven as sole author.

In 1970, after six years at the Chalk River Nuclear Laboratories in Canada, Cowley was appointed Professor of Physics at Edinburgh University. A few years later, the field of phase transitions and critical phenomena was revolutionized with the emergence of Ken Wilson's renormalization group theory. It took Cowley only a few days to see how to adapt these methods to describe the structural phase transition in $SrTiO_3$, and he designed and built an advanced X-ray diffraction instrument to test the predictions. His experiments identified an anomalous form of critical scattering, which became known as the two-length-scale problem. He also made the first measurements of surface truncation rods, and he devised methods to determine the surface and interfacial roughness of thin films. The Edinburgh design of X-ray diffractometer was commercialized and has become a standard analytical tool in industry.

Cowley could see the key experiment to solve a problem, and demonstrated this many times through neutron scattering measurements often performed during summer visits to reactor facilities at Chalk River, Brookhaven, Risø and the Institut Laue-Langevin. He made the first observations of zero-point spin oscillations in an antiferromagnet, studied magnetic structures in rare-earth metals, made a comprehensive map of the cooperative excitations in liquid helium-4, and made the first observation of excitations in helium-3. One of the most original pieces of work concerned the random field problem, a statistical model with applications in glasses, geology and many other areas where random disorder plays a pivotal role. Cowley studied diluted antiferromagnets in a magnetic field and showed that conventional statistical models could not describe the observed response. Not surprisingly, this generated a great deal of controversy, but Cowley behaved calmly and logically throughout, not rising to the bait of the provocateurs, to the great benefit of the science.

In 1988, Cowley was appointed Dr Lee's Professor of Experimental Philosophy at Oxford University, and Fellow of Wadham College. His move to Oxford gave a fresh impetus to his research. One new direction was quantum magnetism, i.e. systems that possess a high degree of quantum entanglement and whose properties are governed by quantum fluctuations, and a seminal work was the observation of fractional spin excitations called spinons on spin-one-half antiferromagnetic chains. A second was the study of metallic films and multilayers grown by molecular beam epitaxy. Cowley exploited X-ray and neutron diffraction techniques he had developed previously to elucidate the structure and magnetic behaviour of these artificial crystals, especially ones made from rare earth elements, such as holmium or erbium alternating with non-magnetic yttrium. These detailed investigations showed that magnetism can propagate from one magnetic layer to another even when the intervening layer is non-magnetic. The work uncovered a large number of exotic and novel magnetic phases and contributed new insights into the theory of magnetism in metals.

Cowley received many awards, including medals and prizes named after Max Born (1973), Holweck (1990), Hälg (2003) and Faraday (2008). He was elected a Fellow of the Royal Society of London in 1978, at the age of only 39, and was also a Fellow of the Royal Societies of Edinburgh and Canada.

Cowley's good nature, quiet determination and energetic commitment extended beyond the leadership of his research group. He was elected Head of Department at Edinburgh twice, and was also twice Chairman of Physics at Oxford. Cowley's style of man-management was based on sincerity, trust and a wry sense of humour. Rather than telling people what to do, he would make little suggestions, then allow people to get on with things.

Cowley's achievements and standing in the scientific community attracted generations of outstanding research students and fellows to work with him. Many of these are now leading researchers at universities and institutes around the world, and remain one of Cowley's enduring legacies.

Amidst all the demands of an academic life and his passion for physics, Cowley still found time to be a devoted family man. He enjoyed playing games with his family or indeed anyone who was visiting. He was an avid tennis player with an unorthodox but highly effective technique. He also loved the outdoors. While on sabbatical leave at Brookhaven National Laboratory he and his family lived on Long Island and were known locally as 'the English who take walks'.

Cowley is survived by his wife Sheila, their children Sandra and Kevin, and six grandchildren.

This obituary was prepared by Andrew Boothroyd with the help of Bob Birgeneau, Bill Buyers, Sheila Cowley, Alastair Bruce, Richard Nelmes, Stuart Pawley, Tom Ryan, Steve Shapiro and Bill Stirling.

COMINGS, GOINGS & AWARDS...

GOINGS...

PROF JOHN CARDY retired in the autumn of 2014. He is one of the greatest statistical physicists of our time and is best known for his ground-breaking contributions to the study of critical behaviour, of the effects of quenched disorder, integrable systems and non-equilibrium critical phenomena. He is a Fellow of the Royal Society, and a recipient of the 2000 Dirac Medal of the Institute of Physics, of the 2004 Lars Onsager Prize of the American Physical Society, of the 2010 Boltzmann Medal of the International Union of Pure and Applied Physics, and of the 2011 Dirac Medal and Prize of the International Centre for Theoretical Physics.

John received his BA (1968) in Mathematics and DPhil (1971) in Theoretical Physics from Cambridge University. After postdoctoral studies at CERN, Geneva and the University of California, Santa Barbara, he joined the faculty at Santa Barbara in 1977. In 1993 he moved to Oxford University as a Senior Research Fellow at All Souls College and a Professor of Theoretical Physics.

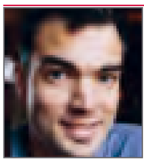
John started his research career in particle physics, but was soon exploiting the interplay between field theory and statistical mechanics to the benefit of both areas. His research has been hugely influential in fields ranging from quantum impurity problems to stochastic Loewner evolution to string theory. His work has regularly inspired other researchers, changed research directions and started or vitalized new fields, via both technical innovations and profound conceptual insights, clarifications and extrapolations. His expository skills, as displayed in his book on the renormalization group and in many elegantly-written lecture notes, have strongly influenced a generation of theoretical physicists.The famous *Cardy formula* for black hole entropy, the *Cardy formula in percolation theory*, and the *Cardy conditions* in boundary conformal field theory are named after him.

After more than twenty years in Oxford, John and his wife Mary Ann decided to return to sunnier climes and recently moved back to California. They will be missed.

AWARDS...

PROF TONY BELL was awarded The IoP Hoyle Medal and Prize for his work on the origin and impact of cosmic rays and for his influential contributions to electron energy transport in laboratory plasmas.

PROF ANDREA CAVALLERI was awarded the 2015 Max-Born Medal and Prize, which is given jointly by the UK Institute of Physics and the German Physical Society, for his pioneering work on THz spectroscopy of strongly correlated materials.



MR JAMES GILBERT was awarded the Leslie H. Paddle Scholarship for his work on robotic systems for the deployment of fibre-optic focal plane pick-off systems in astronomical instruments.

PROF RAMIN GOLESTANIAN was awarded the Société Française de Physique and IoP Holweck Medal and Prize for his pioneering contributions to the field of active soft matter, particularly microscopic swimmers and active colloids.

PROF ISOBEL HOOK shared the 2015 Breakthrough Prize as a member of the Supernova Cosmology Project Team, for 'the most unexpected discovery that the expansion of the universe is accelerating, rather than slowing as had been long assumed'.

PROF DAVID MARSHALL was awarded the IoP Appleton Medal and Prize for his fundamental contributions to understanding the fluid dynamics of the global ocean circulation through the development of penetrating conceptual models.

PROF TIM PALMER, FRS was awarded the IoP Dirac Medal and Prize for the development of probabilistic weather and climate prediction systems; and was named CBE in Her Majesty The Queen's New Year's Honours, for services to science.

We hope you enjoyed reading this issue of the Physics Department's newsletter. To contact the newsletter editor, Prof Fabian Essler, please email newsletter@physics.ox.ac.uk. For latest news on developments at the Oxford Physics Department, see www.physics.ox.ac.uk/about-us.
To contact the alumni office, email alumni@physics.ox.ac.uk.