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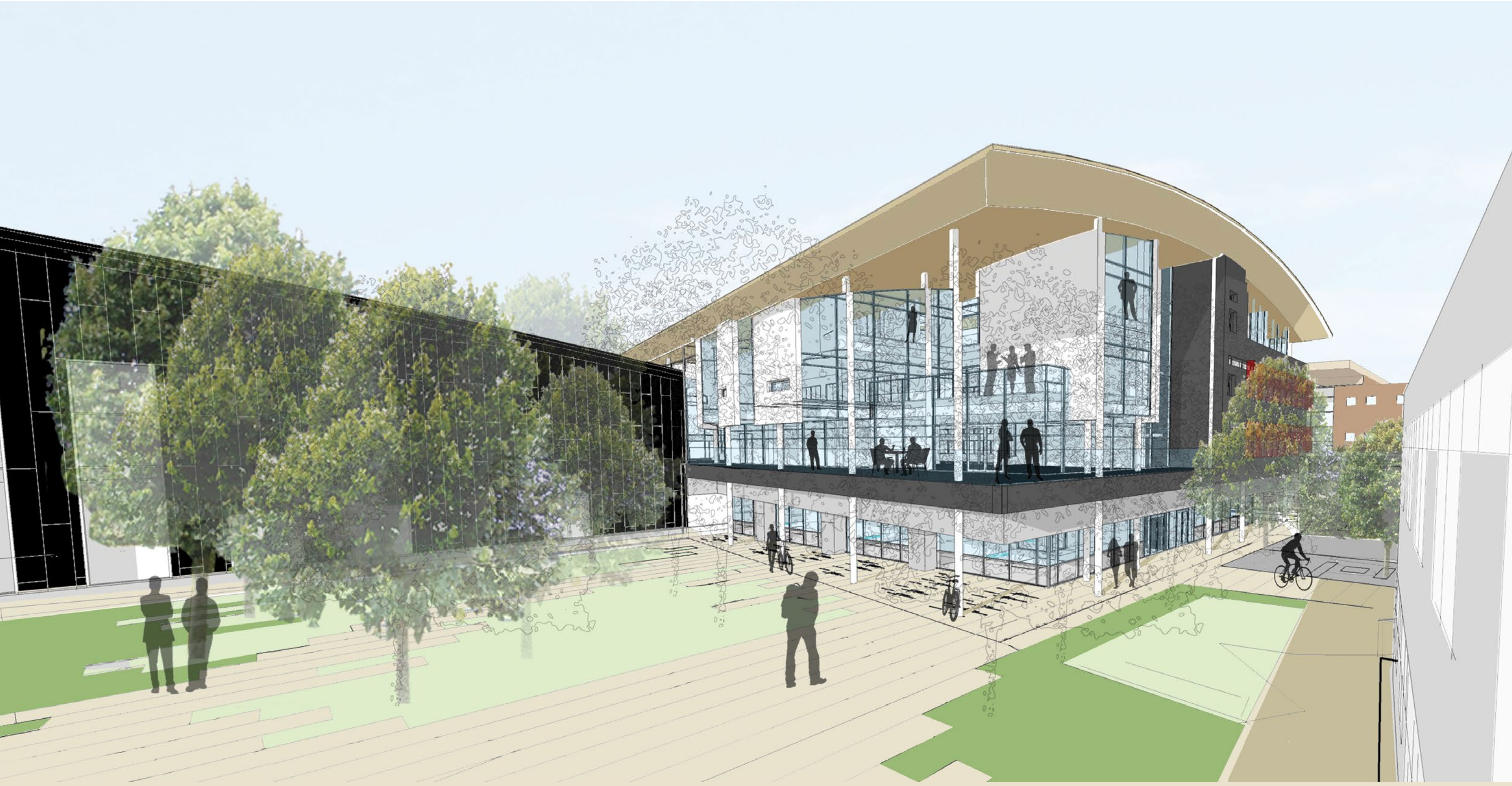
News from the Cavendish Laboratory



The Maxwell Centre

A New £25.6M Building for Industrial Engagement with the Physical Sciences

We are delighted to report a major step forward in the redevelopment of the Cavendish Laboratory with the award of a grant of £21M from the UK Research Partnership Investment Fund 2012-2015 (UKRPIF) of the Higher Educational Funding Council for England (HEFCE) for the construction of the Maxwell Centre. With a further contribution of £4.6M from the University, the Centre will be completed by late 2015.

The announcement was made on 6th June 2013 in a press release by HEFCE which stated:

- A £63 million partnership between the University of Cambridge, the Winton Programme for the Physics of Sustainability, Hitachi Ltd, the Herchel Smith Trust Fund and others to build The Maxwell Centre. This will be a centrepiece for industrial partnership in the physical sciences on the West Cambridge Science and Technology campus, increasing collaboration with SMEs and acting as a hub for graduate training.

The four main objectives of the UKRPIF scheme are to:

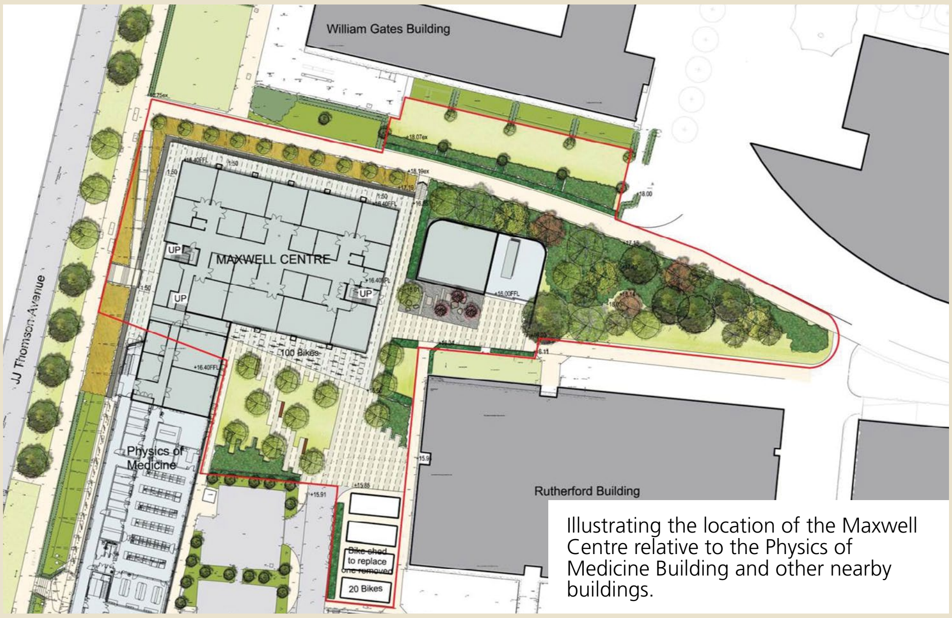
- Enhance the research facilities of higher education institutions (HEIs) undertaking world-leading research
- Encourage strategic partnerships between HEIs and other organisations active in research
- Stimulate additional investment in HEI research
- Strengthen the contribution of the research base to economic growth

Continued overleaf...

Main image: An architect's impression of the Maxwell Centre from the South showing the Researchers' Garden and the Physics of Medicine Building.

Continued from overleaf

The rules of the scheme were that funding was to be allocated on the basis that HEIs have secured at least double the funding requested from co-investors, meaning non-governmental sources. Thus, for every £1 from the UKRPIF, there should be an additional £2 invested from these sources. Thanks to the generosity of our donors, which include major philanthropic gifts from the Winton programme, Hitachi Ltd., Toshiba Ltd., Herchel Smith Trust Fund, the Raymond and Beverly Sackler Foundation and Tata Steel (to the Materials Science Department) and to our large portfolio of research contracts with industry, we demonstrated that we have secured a guaranteed minimum of £42M of non-governmental funding for the coming years.



Illustrating the location of the Maxwell Centre relative to the Physics of Medicine Building and other nearby buildings.

Of central importance to the success of the bid was the gift by David Harding of £20M to create the Winton programme, which in its scale and unrestricted scope matched perfectly the intentions of the scheme and will form the core of activities in the new building.

George Osborne, Chancellor of the Exchequer, said: 'By bringing together our Nobel Prize winning scientists, our world-class companies and our entrepreneurial start-ups, we can drive innovation and create the economic dynamism Britain needs, using public money to secure private investment so that our world-class science also delivers jobs and growth.'

David Willetts, Minister for Universities and Science, said he believes this project will 'not only deliver new knowledge and applications for industry, but will accelerate growth and foster innovation between the research base and business, keeping the UK ahead in the global race.'

Professor Sir Leszek Borysiewicz, Vice Chancellor of the University of Cambridge, said: 'The University has already invested very heavily to build up our research base on the West Cambridge science and technology campus, and through the Maxwell Centre, we will capitalise on this resource by embedding industrial engagement still further into the University.

'Links between new science and real applications are very well established in the Physical Sciences. This is evident from the very large and diverse set of industrial partners who are co-investors in the Maxwell Centre. We are determined that the Maxwell Centre will be the centrepiece for a very substantial growth in our industrial engagement in the Physical Sciences. This builds on real excellence in research, an outstanding student base and very strong and enthusiastic collaborations with a broad range of industries.'

This will not be conventional research or 'business as usual', but a major effort to go beyond the boundaries of traditional physical science concepts. The key to innovation is an effective bottom-up approach to fundamental research. We will combine work on the specific challenges facing collaborators with research into areas at the edges of current conception – the 'unknown unknowns'.

What will happen in the Maxwell Centre? A major emphasis of the proposal is that the Maxwell Centre will involve 'blue-skies' research, most of the activity involving core Cavendish basic research. The key innovation is the central role of industrial liaison and the accommodation of our industrial collaborators within the building. This will involve both the undertaking of experiments and the interpretation and exploitation of the results of innovative types of experiment and theoretical investigations. There will be a strong emphasis upon the role of Scientific Computing and the needs of industry. We will enhance our existing collaborations with our colleagues in Materials Science and Chemistry in cognate areas of research. Accommodation will be provided for students who enter courses supported by the Centres for Doctoral Training.

The space available in the building will house about 230 research staff and students and will be allocated on the basis of the excellence and innovative nature of the science with an emphasis on industrial-focussed research and participation.

A substantial fraction of the building will involve new projects originating from within the existing research groups in the Physical Sciences. They will bring their own programmes, which have received 'pump-prime' funding from the Winton programme and other sources, to initiate projects that extend the range of their scientific endeavours.

This is a key step in the Cavendish's redevelopment programme and we are enormously grateful to our benefactors for their generosity and to our industrial sponsors for their support of and continuing confidence in our joint research ventures.

Richard Friend and Malcolm Longair

An architect's impression of the Maxwell Centre from the approach along JJ Thomson Avenue

Clerk, Maxwell, Clerk Maxwell and Maxwell Clerk

The proposal that the new centre for the interaction between industry and the physical sciences should be designated the Maxwell Centre was adopted early in our plans. We sought an inspiring designation which would reflect the breadth of the vision for the new Centre, whilst honouring the first Cavendish Professor of Experimental Physics.

Maxwell was a genius both as a theorist and an experimenter and proved to be the essential link between the physics of Newton and that of Einstein. Through the discovery of Maxwell's equations for the electromagnetic field, the concept that fields underlie the structure of physics was embedded in a very profound way and the scene set for the development of Einstein's General Relativity and Quantum Field Theory. But Maxwell's vision was much wider than simply fields – he introduced statistical concepts into thermodynamics, was an expert on knots and made brilliant contributions to the tricolour theory of colour vision. In all these areas, he had a profound belief in the practical application of physics for the benefit of society.

Maxwell's name has not been honoured by the naming of any building in the Cavendish Laboratory, despite the fact that he designed the original Laboratory in Free School Lane and was responsible for the regeneration of physics research in Cambridge. Within a couple of decades, the Cavendish was regarded as the premier physics laboratory worldwide, thanks to the genius of the Cavendish Professors.

With our success in winning UKRPIF funding for the Maxwell Centre, I wrote to the current head of the Clerk family, Sir Robert Maxwell Clerk, as follows:

> *'We would be delighted if you were happy with the use of the Maxwell name for the new building. My contacts with the Trustees of the JCM Foundation have elicited enthusiastic responses and I hope you would also regard this as a suitable acknowledgement of the greatness of James Clerk Maxwell. …*
>
> *We like the term Maxwell Centre, but there is the question that Clerk Maxwell is the family surname. In the physics literature it is always Maxwell's equations, the Maxwell distribution, Maxwell's demon and so on. So, simplicity has its merits. It would be interesting to hear your views.'*

In reply, I received the following response from Sir Robert:

> *'Dear Malcolm*
> *… I am delighted to hear of the award of this substantial grant to the Cavendish Laboratory and the proposal that the new building be named the 'Maxwell Centre'; it is interesting that in the last few years so much recognition has (at last!) been given to the hugely important work of James Clerk Maxwell.*
>
> *Of course it would be nice if the new building were to be known as the 'James Clerk Maxwell Centre' but I fully understand that that may be a bit of a mouthful and more particularly that he has consistently been referred to as 'Maxwell' in relation to the equations etc. So, adopting a pragmatic attitude, I can only welcome this proposal and hope that the new building will prove to be as important in the field of research and of benefit to British industry as the press release suggests. It seems very fitting that the purpose of this new building will be to promote innovative research in a wide range of areas of science from which tangible benefits can be derived. I am sure JCM would approve!*
> *Kind regards*
> *Robert'*

I am often asked about the origin of the name Clerk Maxwell and its relation with the Clerk Family. The following explanation comes from David Forfar's essay[1] on the many ancestors of Maxwell who were fellows of the Royal Society and/or of the Royal Society of Edinburgh. I have added their dates and mild annotations for clarification.

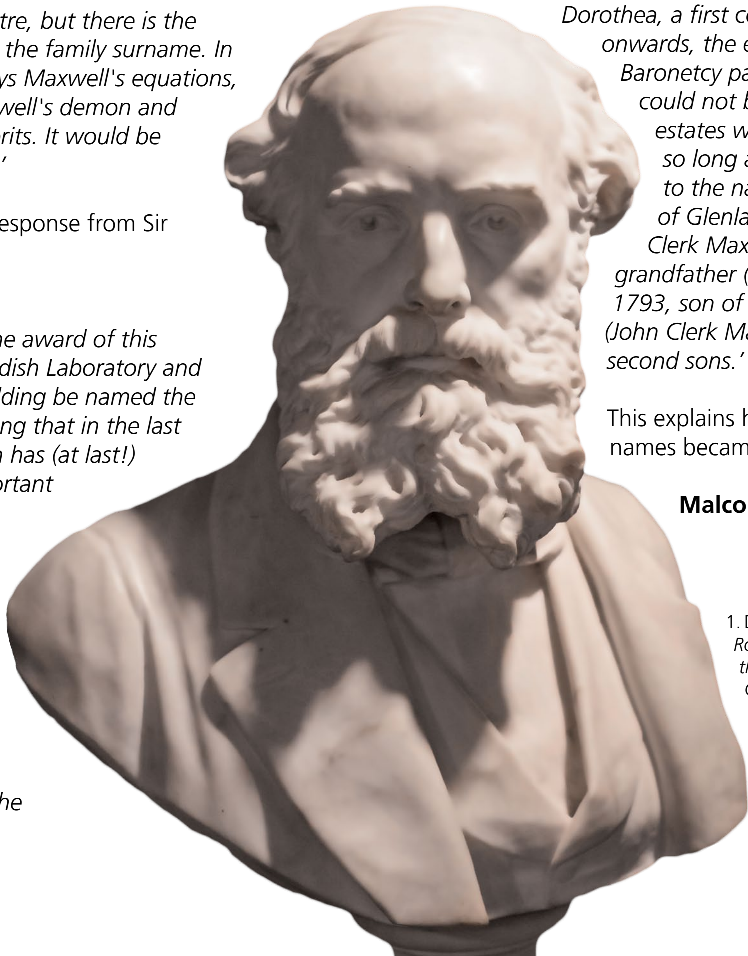
There are two estates involved. The Penicuik estates are close to Edinburgh and are where the current head of the family, Sir Robert Maxwell Clerk, resides. The Middlebie estates are in the south-west of Scotland, not far from Dumfries and the house there is named Glenlair. The latter are the estates which were to be looked after by James Clerk Maxwell and the house where he wrote his great 'Treatise on Electricity and Magnetism' is at Glenlair. Maxwell was buried at the nearby village of Parton.

David Forfar wrote:

> *'The name Maxwell entered the (Clerk) family in the following manner. The brother of Sir John Clerk (2nd baronet; 1676-1755), William Clerk, had married Agnes Maxwell, heiress to Middlebie Estate, and they had a daughter Dorothea. Sir George Clerk (1715-1784, son of Sir John Clerk) married his cousin Dorothea, a first cousin marriage. From Sir George onwards, the estates of Penicuik and the Baronetcy passed to the first Clerk son and could not be held along with the Middlebie estates which passed to the second son, so long as the name Maxwell was added to the name. Thus the Middlebie Estate of Glenlair passed down to (our) James Clerk Maxwell (1831-1879) through his grandfather (James Clerk Maxwell c.1740-1793, son of Sir George Clerk) and father (John Clerk Maxwell 1790-1856), who were all second sons.'*

This explains how the Clerk and Maxwell family names became intertwined.

Malcolm Longair



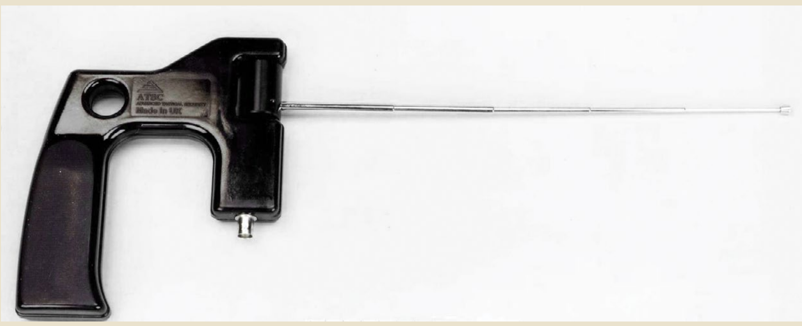
1. David Forfar, 2008. *Clerk Maxwell and the Royal Society of Edinburgh.* In *Celebrating the Achievements and Legacy of James Clerk Maxwell*, (ed. David Forfar), 11-49. Edinburgh: The Royal Society of Edinburgh.

Sutherland of the Bailey

Michael Sutherland appeared as a prosecution witness in the case of the UK businessman Jim McCormick who was tried at the Old Bailey earlier this year. Michael reflects on his experience in an extraordinary case of fraud and the abuse of science.

The years following the Iraq war were a terrible time to be in Baghdad, as a wave of violence enveloped the capital and threatened to propel the entire country into a bloody civil war. Deadly suicide bombings were a daily occurrence and thousands of innocent Iraqis, going about their business in busy markets or workplaces lost their lives in a series of explosions. The death toll was staggering. In a single day in March 2010 for instance 100 people were killed and 350 injured.

The fact that these bombings occurred in crowded urban conditions made them difficult to detect and counter, and Iraqi officials were desperate for a quick-fix solution. In the eyes of the military this came in the form of the ADE-651, a handheld bomb detection device sold by Jim McCormick, a UK-based businessman. The technical specifications for this device were truly remarkable - far beyond what existing technologies could achieve. In the marketing literature it was claimed that the ADE-651 could detect explosives at picogram levels, from a distance of several kilometers through concrete walls, under 30m of water and even from a moving airplane.



The device was simple enough. It consisted of a molded plastic handle with an antenna affixed to one end that was free to swivel in an arc. A coaxial cable ran from the handle to a pouch worn on the user's waist. By placing different cartridges in the pouch the functionality of the device could be extended to detect various contraband – narcotics, ivory, even money. It was claimed all of this was possible without the need for sophisticated electronics or even a power source, as the ADE-651 could run on the static electricity provided by the operator as they walked.

As outlandish as these claims seem, the ADE-651 was an astounding commercial success. Orders poured in from Iraq for the £25,000 units, and they were in wide use across the country. McCormick grew extremely wealthy, extremely quickly. By 2011 it is estimated that he had made a profit of £60 million from selling these devices, buying a luxury yacht and a £4 million house from Hollywood actor Nicolas Cage.

Eventually the spiraling body count from Iraq spurred rumours about the effectiveness of the devices. Some soldiers on the ground doubted their capabilities, and the media became interested. Pressure mounted on authorities in the UK to take action and an export ban was placed on the ADE-651, with fraud charges filed against McCormick in 2012.

In 2010 the Metropolitan Police approached me to give an independent scientific assessment of the device's effectiveness. My research in the Quantum Matter group involves detecting very small electronic signals, and I was tasked with both reviewing the operating principle of the ADE-651, and conducting field trials to search for explosives.

As might be expected, the technical literature was vague on details, with sections cut and pasted from Wikipedia. An electromagnetic signal was said to be emitted from the device at a resonance frequency of the substance in the field, which caused the antenna of the ADE-651 to point in the direction of the explosive. This immediately raises several questions. With no power source or electronics how can you generate a propagating electromagnetic wave? Why should the substance absorb radiation at only one resonance frequency and what determines its value? What is the force that causes the antenna to move and how can this force be sizable given a kilometer separation between the detector and substance?

Double-blind field trials were conducted with the help of Cavendish graduate student, Lina Klintberg, at a disused military facility. A sample of TNT was randomly placed in one of 6 identical boxes, and unsurprisingly we found that in 24 trials we had only 3 successful detections, no better than what is expected from random chance.

Despite the evidence, securing a conviction was not straightforward. The prosecution needed first to demonstrate to the jury that the devices could not work, and second to show that McCormick knew they could not work. The case came to the Old Bailey in April 2013, amidst considerable media interest.

Testifying at the Old Bailey was a daunting prospect, but in some ways I found it similar to a Cambridge supervision - technical concepts had to be explained carefully and fully without ambiguities, in a manner that was clear and accessible to the court. The questioning and cross examination went on for several hours, with questions ranging from the elementary 'what is an electric dipole' to the arcane 'what does the BNC in BNC connector stand for?' Experts in radio engineering and bomb detection were also called and our testimony was weighed against witnesses for the defense. Thankfully, the jury

CASTEP achieves $30 million in sales

A software tool which uses quantum mechanics to allow designers to predict the properties of materials has reached the commercial milestone of $30 million in sales. Mike Payne was recently interviewed by Sarah Collins of the Office of Communications about the success of CASTEP.

CASTEP, based on the research of Professor Mike Payne and his colleagues in the Theory of Condensed Matter Group, is a software product which allows researchers to determine what the most stable structure of a new material would be, what its surfaces will look like and how the bulk and the surface will behave when exposed to different chemicals. CASTEP is widely used in the oil and gas, chemical and semiconductor manufacturing industries, where along with other techniques, it can be used to enhance the efficiency of processes, and help identify the origin of failures in devices and products.

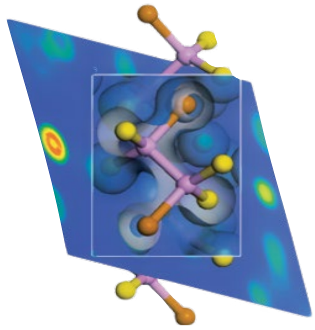
The code uses the principles of quantum mechanics to describe phenomena at the atomic level. Using quantum mechanics enables different properties of a material to be determined in a computer, allowing researchers to peer inside a figurative Schrödinger's box. The software is based on density functional theory, which is used to describe the systems of electrons in which the energy is directly related to the density of those particles. Researchers can 'pour' electrons into the CASTEP box and the software works out how the electrons will be distributed and, from this, determines the energy of the system. It can also tell whether the atoms are located where they should be or not, and can help to move the atoms to more favourable arrangements if desired. CASTEP can also predict many different spectra, such as infrared or nuclear magnetic resonance (NMR), allowing many different characteristics to be determined using a single piece of equipment.

'It was basically the first materials code where all of the complexity was taken out and you were left with a black box that is rigorous, robust and reliable,' says Professor Payne. It was also the first such code to be made available on parallel computers, allowing many processors to be used simultaneously, providing access to much larger and more complex systems.

CASTEP is another high-profile software success to come from the Cambridge cluster, home to more than 300 software companies, including the $10 billion company ARM. The code was first licensed by Cambridge Enterprise, the University's commercialisation arm, to Cambridge-based software company Accelrys in 1995, and has recently passed $30 million in sales.

"When CASTEP came along, for the first time you could learn something about the system before the system is even made."

Mike Payne



It is unusual for a piece of software to be so long-lived. 'Software can have that sort of lifespan, but you can't stand still,' says Professor Payne. 'The thing about academic software is, if you do it right, there need not be any delay between academics developing new capabilities and functionalities for the software and providing exactly the same capabilities to the commercial customers.'

Professor Payne attributes the product's success to a continuous process of development and improvement which included a complete re-write of the code by the CASTEP Developers Group between 2000 and 2003. 'In contrast to the code re-writes in the ASCI programme in the United States, in which each re-write cost $25 million, CASTEP was re-written by six people in their spare time at a fraction of that cost.' The code is free for any UK-based academics to use, and more than 750 academic papers based on CASTEP calculations were published in 2012. Commercial sales and a recently launched low cost European academic release are handled by Accelrys. A potential area of future growth for CASTEP is in the pharmaceutical industry, where it is starting to be used in combination with solid-state NMR to detect impurities in drug molecules.

Since the development of CASTEP, the cost of performing calculations has become so low that tens of thousands, or even millions, of calculations can be performed. There are now significant opportunities for exploiting this using the data mining techniques developed in other fields. With the volume of calculations that are now possible, researchers may soon be able to design a new material based on the properties they would like it to have, rather than determining the properties of a material which already exists.

Professor Payne warns that CASTEP cannot however solve the paradoxes of quantum mechanics or deal with all the complexities of materials behaviour on its own. 'CASTEP is a tool to help us understand very complicated problems,' he says. 'Occasionally, it can solve the problem by itself, but the reality is the more tools you can bring to bear on such complex problems, the better.'

Mike Payne is Professor and Head of Theory of Condensed Matter

swiftly reached a guilty verdict and McCormick was sentenced to 10 years in custody, with his assets seized under the proceeds of crime act.

I take two lessons from this experience. First, there is a great deal of trust and respect for science in the general public, and as such scientists should strive to be able to communicate with the non-expert. Second, I see great importance in maintaining a basic level of scientific literacy in the general public. Not everyone will go on to study physics at university of course, but familiarity with the most basic laws of electricity and magnetism might have raised doubts amongst those purchasing the ADE-651, and might even have saved lives.

Michael Sutherland is a Royal Society University Research Fellow and works in the Shoenberg Laboratory for Quantum Matter.

Image, top-centre: Iraqi and U.S. soldiers carry out random security checks during a security checkpoint mission in Abu T'Shir, Iraq. Credit the United States Navy.

Image, bottom-centre: the ATE-651 device.

Climbing staircases one atom at a time: towards 3-dimensional microchips

When he arrived at the Cavendish three years ago, Russell Cowburn described in CavMag5 his ambitions for creating three-dimensional magnetic semiconductor devices. He has now delivered on that promise with remarkable potential for the future, as he describes below.

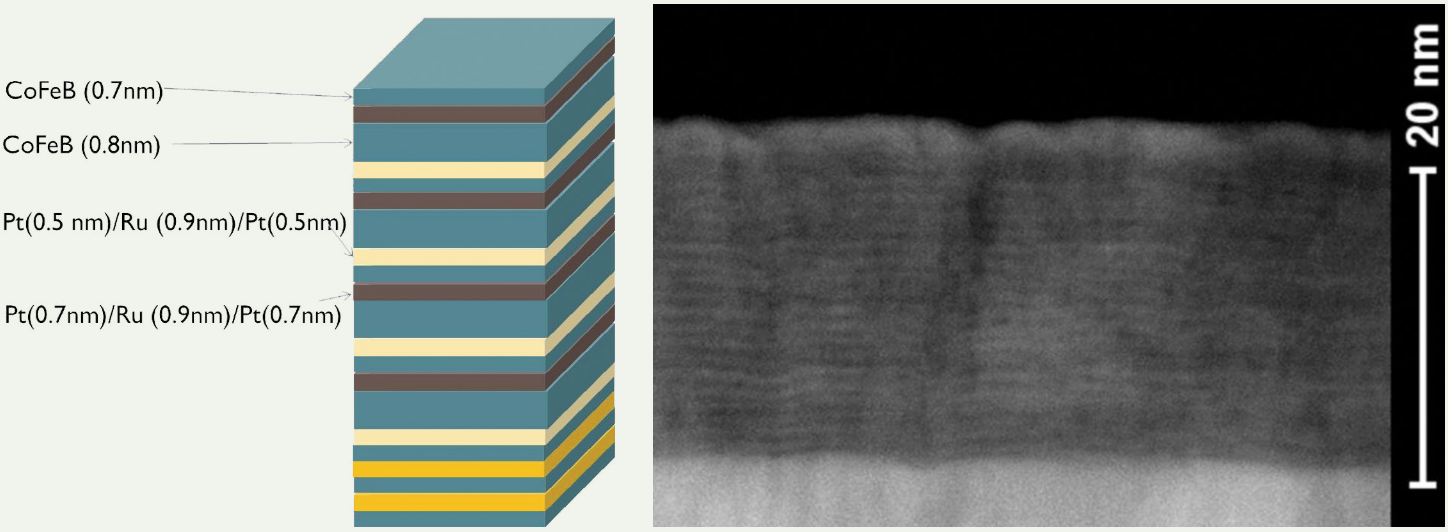
Today's microchips are essentially 2-dimensional structures. Although each chip has a complex network of electrical conductors that run up and down as well as laterally, those conductors connect a 2-dimensional mesh of transistors. Consequently, the processing power or memory storage capacity of a chip scales as F^{-2}, where F is the smallest structure size that can be made on the chip. This has served us very well for several decades now. Each year, engineers reduce F by a few tens of percent by using increasingly complex lithography machines with ever shorter wavelengths of light to fabricate the devices, allowing more and more to be packed into the same area. But what if we could change the scaling law from F^{-2} to F^{-3}? Improvements in chip performance would be measured in factors of 1000s instead of tens of percent. In practice this would mean moving from a 2-dimensional mesh of transistors to a 3-dimensional lattice of data processing elements.

Engineers have dreamed of this for some time, but it is not a trivial task. The closest anyone has ever come commercially is in 2.5-dimensional structures, in which a number of circuit boards or silicon wafers are bonded on top of each other. Apart from the problem of how to fabricate a true 3-dimensional structure, there are enormous challenges in how to extract the heat generated in the centre of the lattice – today's planar chips are already at their thermal limits and that is with enhanced cooling that comes from having a large surface area to volume ratio. Pack all of those heat generating elements into a confined volume and the silicon would melt. Handling the complexity of wiring in a 3-dimensional volume is a further challenge – each cell needs power, ground, a clock etc.

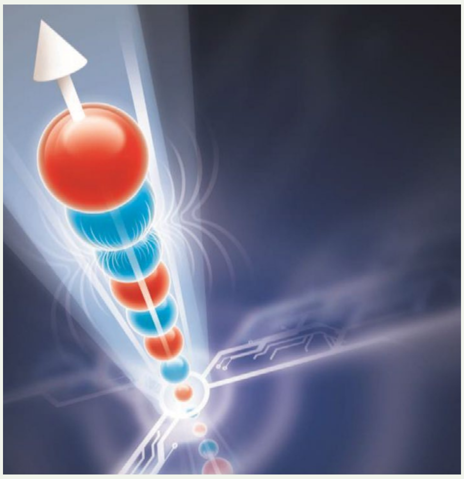
In a recent paper in *Nature*[1], my research group described its latest work in trying to overcome some of these difficulties to make a true 3-dimensional microchip. We chose to work using a new type of chip technology called *spintronics*, in which magnetic materials are combined with conventional semiconductors to harness both the charge and the spin of the electron. This helps enormously with the heat dissipation problem. Changing a data bit in a charge-based device requires a relatively large packet of energy to be dissipated, due mainly to the fact that semiconductor switches operate at a voltage that is large compared to the basic thermodynamics of the electron. In contrast, the spin of an electron can be reversed using an amount of energy that approaches the Landauer limit – the smallest amount of energy thermodynamically possible to achieve the task. Spintronics also allows information and power to be passed using indirect means – for example, using a magnetic field or the extended wavefunction of an electron. This helps with wiring complexity. Finally, we ignored the conventional approach to creating high-level digital functions in chips, namely building them up from simple transistors, and instead attempted to harness the properties of advanced materials to extract complex logic functions from the intrinsic properties of the materials themselves.

The logic function we implemented was a 4-stage serial shift register. A shift register is a device which passes data along a chain of memory cells. It has only one input and one output but there can be several memory cells connected in series between these two points. To ensure that data always passes in a well-defined direction and does not diffuse backwards and forwards, shift registers usually make use of a design known as 'master-slave': information is taken into the first half of each memory cell (the 'master') on the rising edge of a clock pulse and then passed to the second half of the cell (the 'slave') on the next falling edge. Think of a kissing gate on a country footpath.

Our 3-dimensional spintronic shift register was made of layers of magnetic and non-magnetic materials only a few atoms thick stacked on top of each other. The magnetic layers (an alloy of cobalt, iron and boron) are the memory cells, and the interleaving non-magnetic materials (a tri-layer of platinum, ruthenium and platinum) are the connections. Unlike simple copper connections on a conventional chip, the Pt-Ru-Pt connectors act like an



A schematic (left) and a high resolution transmission electron micrograph (right) of the spintronic shift register. TEM courtesy of Dr J.H.Lee.



Passing spintronic data atom by atom.

optical interferometer for the electron wavefunctions, coupling neighbouring magnetic layers in a strong and precisely defined way. We achieved the master-slave functionality by varying slightly the thicknesses of the layers: magnetic layers alternated between 0.7nm and 0.8nm thick and the platinum layers alternated between 0.5nm and 0.7nm thick. This particular structural form creates a ratchet-like energy profile as one traverses the layers, allowing information to be moved only from the bottom of the stack to the top.

Using a laser magnetometer we were able to inject a data bit at the bottom of the layer structure and then watch it climb layer by layer on progressive cycles of a clocking magnetic field. Four cycles later it popped out of the top of the structure.

This is an early stage physics lab demonstration of what might be possible on a large commercial scale in the future. Our chip only had one memory cell (laterally), compared to the billions present in proper chips. But in passing vertically a single bit of data through four shift-register stages we achieved the equivalent of approximately 40 transistors stacked on top of each other. And the distance from the input to the output of each of our shift registers was only 5nm – a good two orders of magnitude smaller than state of the art microelectronics. In showing how complex functions can be implemented from carefully constructed layers of materials, we are potentially opening the door to a range of other applications beyond microchips, including industrial sensors and biomedical applications.

Professor Russell Cowburn is Director of Research in the Thin Film Magnetism Group.

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1. Lavrijsen, Lee, Fernandez-Pacheco, Petit, Mansell and Cowburn, Nature, **493**, 647 (2013).

Quantum Matter Research in the Cavendish Laboratory

"Could anything at first sight be more impractical than a body, which could only exist in vessels from which all but a minute fraction of the air has been extracted [...] ?"

J. J. Thomson on the discovery of the electron

Quantum liquids
In an age of coal and steel, industrial sponsors might have taken a dim view of the experiments undertaken by J. J. Thomson and his contemporaries on the nature of the electron. A generation later, when an entire industry had grown around the use of vacuum tubes, few people again would have seriously considered the prospects of replicating these devices in solids. But because in high purity crystals electrons can travel over long distances without scattering – replicating properties of the vacuum in the solid state – it was found that semiconductor devices allow electrons to be controlled and manipulated to a previously unimagined degree, enabling the modern electronics, telecommunications and computing industries.

Whereas in semiconductors the mobile electrons are strongly diluted, electrons in metals form a dense, interacting liquid. We speak of quantum matter, if quantum statistics rather than classical statistical physics are required to describe a system. The cross-over to quantum statistics occurs, when the thermal de Broglie wavelength, λ , becomes larger than the typical separation between the particles. Taking $\lambda \propto 1/\sqrt{mT}$, where m is the particle mass and T is the temperature, this implies that for three-dimensional systems, quantum statistics make themselves felt below a cross-over temperature, or degeneracy temperature, which depends on the particle number density and on their mass as $T_d \propto n^{2/3}/m$. The high number density and low mass of electrons in metals translates to very high quantum degeneracy temperatures, usually well above room temperature and exceeding the surface temperature of the Sun in many cases. This implies that quantum effects are fundamentally important and, combined with the increased relevance of electronic interactions in dense systems, opens up new possibilities for exploitable electronic quantum effects.

One of the biggest scientific surprises of the twentieth century was the discovery of superconductivity. Frictionless flow of electrons appears impossible in classical physics, but some aspects of microscopic objects such as atoms can be interpreted in terms of persistent quantum zero-point motion. By lifting phenomena we normally associate with the exotic micro-world of quantum physics into the practical macro-world of cables and switches, the discovery of superconductivity has paved the way for new devices and applications, such as magnetic resonance imaging scanners, high current fault limiting switches and high frequency filters.

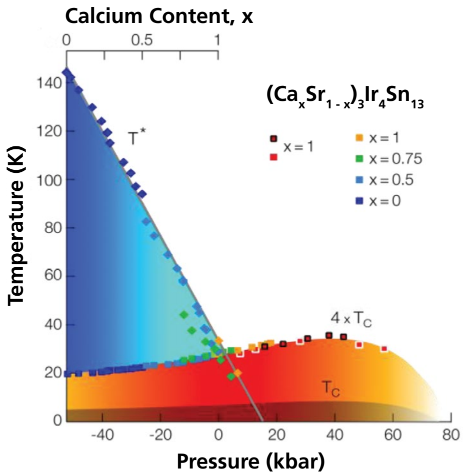


Fig. 1: Phase diagram of the cubic metal $(Ca/Sr)_3Ir_4Sn_{13}$. The parent compound $Sr_3Ir_4Sn_{13}$ undergoes a second-order structural transition at a temperature $T^* \approx 150$ K and a superconducting transition at $T_c \approx 5$ K at ambient pressure. Both partial substitution with Ca and applied hydrostatic pressure reduce T^*. This affects the phonon spectrum and thereby influences both the superconducting transition temperature, which nearly doubles, and the normal metallic state, in which increased phonon scattering causes an anomalous temperature dependence of the resistivity [L. E. Klintberg, S. K. Goh *et al.*, Physical Review Letters, 109, 237008 (2012)]

Tunability of many-particle systems
Superconductivity presents an example of how interactions between electrons cause them to correlate their motion and induce new ordered states. Although in a microscopic, high energy description the only relevant interaction is the electrostatic Coulomb interaction, low energy models generate *effective* interactions, which can have entirely new properties. For example, the effective interaction between noble gas atoms is described by the van der Waals potential, the effective interactions between electrons in magnets are spin dependent and in superconductors they

have an attractive component. Effective interactions depend on details and thereby become highly tunable: they can be varied by changing material composition, by applying magnetic or electric fields, or by changing the lattice spacing through applied pressure. They may favour a particular type of low temperature order in one region of parameter space, and different ones elsewhere (see, for example, Fig. 1). The transition into a new ordered phase at low temperature as a function of this form of quantum tuning is called a *quantum phase transition*. The vicinity of quantum phase transitions provides a fertile ground for unexpected and often spectacular discoveries. Recent examples include high temperature superconductivity in the iron-pnictide materials, the quantum nematic state in $Sr_3Ru_2O_7$, and unconventional superconductivity in uranium-based ferromagnets.

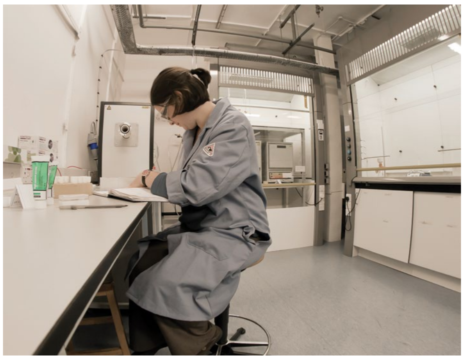


Fig. 2: Winton Fellow Siân Dutton in the main Quantum Matter crystal growth laboratory.

Plenty of room in material space

While there are only about one hundred elements, the space of compounds is exponentially large. Might electronic self-organisation give rise to a similarly explosive growth in possibilities? New states of matter of current interest include various unusual particle-hole condensates, such as spin or charge Pomeranchuk order, which involves anisotropic deformations of the Fermi surface, and novel forms of unconventional superconductivity, or electron-electron condensates, in extreme cases potentially even at room temperature. Beyond this classification, distortions of order parameter fields can be expressed in terms of topological invariants. Examples include defects and defect structures, such as flux lines in superconductors, skyrmion lattices in certain chiral magnets and magnetic monopoles in spin ice materials, as well as the recently discovered topological insulators.

Quantum Functional Materials

The diversity of these phenomena, their intrinsic quantum nature, their reach into practically useful temperature regions and their tunability can be exploited for next generation quantum innovations. These may be novel devices, for instance for sensing, computation or storage, or new materials to be used as battery electrodes, capacitor dielectrics, memory elements, superconductors, Peltier coolers or thermal energy harvesters, or for magnetic refrigeration. QM members are exploring new materials, in particular for sustainability applications (Fig. 2), and growing high purity crystals of candidate materials for detailed investigation.

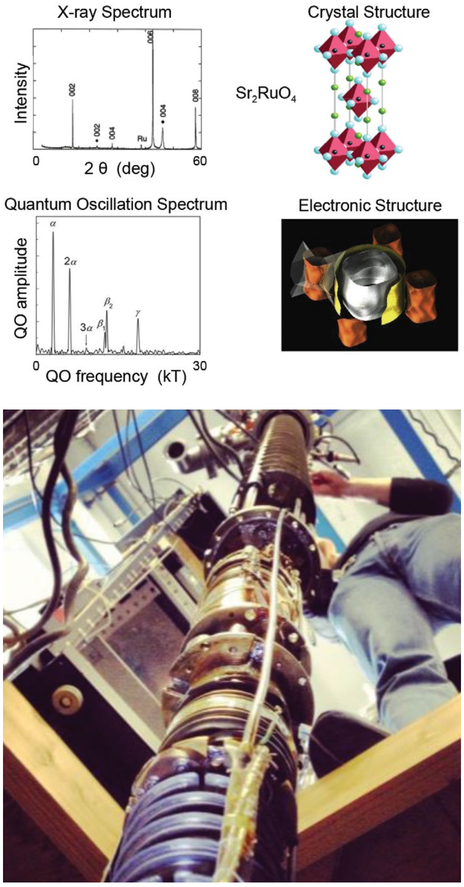


Fig. 3: (Top) Analogy between the roles of x-ray diffraction and quantum oscillation (de Haas van Alphen or Shubnikov de Haas) measurements. (Bottom) The low temperature insert of the Quantum Matter group's 18 Tesla, 1 mK cryomagnet facility (with Marie Curie fellow Sven Friedemann) from the point of view of a sample soon to be cooled down (photo by Michael Sutherland).

To pave the way for future discoveries, we need to understand the mechanisms operating in materials near known electronic instabilities. Key information is obtained by examining the electronic structure. This is analogous to finding a material's crystal structure. Because the electrons are always in motion, we do not determine their position but rather examine the relationship between their momentum and energy by observing the electronic Fermi surface and effective mass. We can achieve this by mapping out oscillations in the magnetic field dependence of the electrical resistivity, the magnetic susceptibility or other material properties at low temperature (Fig. 3). QM group members Suchitra Sebastian, Gil Lonzarich and John Cooper have recently made key contributions to the determination of the electronic structure of copper oxide high temperature superconductors using this technique. Moreover, we increasingly apply it to study the electronic structure near pressure induced quantum phase transitions. To achieve the required ultra-sensitive measurements at pressures of tens or even hundreds of thousands of atmospheres is challenging, but it is made possible by recent technique developments (Fig. 4). These studies will help to clarify long-standing questions, such as the nature of the metallic state on the threshold of Mott metal-insulator transitions or in correlated semimetals, and may help identify new types of topological insulators. Beyond these objectives waits a multitude of unknown, truly novel states of quantum matter, which only experiment can bring to light.

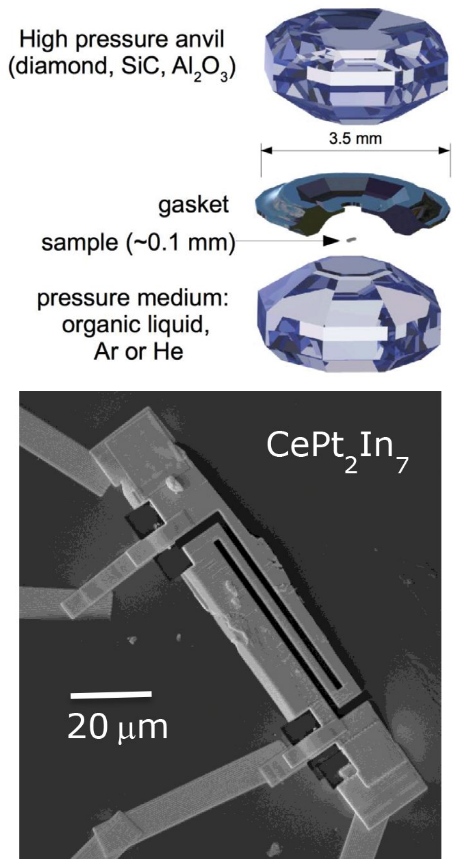


Fig. 4: (Top) Key components of a gem-stone anvil high pressure cell. (Bottom) Sample handling on the microscale. A sample of a pressure-induced superconductor has been shaped and contacted by focussed ion beam techniques on the surface of a high pressure anvil for Fermi surface measurements under pressure (collaboration with Jakob Kanther, ETH Zürich).

Malte Grosche

Malte Grosche is Reader in Low Temperature Physics and Head of the Quantum Matter Group

Andy Parker takes over the reins from James Stirling


James Stirling arrived as Jacksonian Professor of Natural Philosophy in October 2008 and became Head of Department in April 2011. We congratulate him most warmly, but with sadness, on his appointment as the first Provost of Imperial College London. This is a magnificent appointment and we wish him well in this huge challenge. We are delighted that Andy Parker has agreed to take over as the new Head of the Cavendish Laboratory from 1 August 2013.

The role of Head of the Cavendish Laboratory is a major commitment. It is a far cry from the days of JJ Thomson when the finances of the Laboratory could be run from the personal bank account of the Cavendish Professor. Nowadays, the only sensible way of regarding the position is as that of the CEO of a company of almost 1000 people, subject to the strict rules of University and Government management and accounting. Everything is ultimately the responsibility of the Head of Department. Nonetheless, it is a wonderful position and gives the post-holder the opportunity to contribute in major ways to the future development of the Department and Physics in its broadest sense.

There is never anything like a 'steady-state' in the operation of a large physics department and the challenges change from year to year. In reflecting on his time in the Cavendish, James Stirling has remarked:

'*History may record that my tenure as Head of Department was the shortest to date, but it has been a real pleasure and a privilege to have served the Department over the past two years, and to have stood albeit briefly on the "shoulders of giants". Just after I took up office in 2011, I wrote in CavMag6 about some of the opportunities and challenges that the Department faced at that time. Reading those words again, I am pleased that a number of initiatives are already bearing much fruit. The Winton Programme is now firmly embedded in the Department, and its community of outstanding early career researchers is growing steadily. The new Battcock Centre for Experimental Astrophysics building is almost ready for occupation, and relations with our friends and colleagues across the road in the Institute of Astronomy are growing stronger all the time. The Department's Physics of Medicine programme is now part of an exciting pan-University 'Physical Biology' initiative. Not all of our recent successes were anticipated, however. Success in HEFCE's 2012 infrastructure funding competition has enabled us to embark on the new Maxwell Centre programme and building, as described elsewhere in this edition, and our overall plans to redevelop the whole Laboratory remain well on track. The number of undergraduates studying physics here is now at an all time high, I believe in large part due to our excellent schools outreach programme. Our position as one of world's top physics departments is fully deserved, but should never be taken for granted.*

One of my aims was to improve the support we provide for our research staff, especially those at an early career stage, and to address the still unacceptable gender imbalance in the Department, and indeed in the subject nationally. I will be keeping my fingers crossed that our recently submitted application for Athena SWAN Gold status will be successful, and I would like to thank all those colleagues who have contributed so much to making the Department a better place to work for all.

There are so many other highlights that come to mind: the large number of prizes, awards and grants that colleagues have won; the many VIP visits that the Department has hosted; the world-leading academic colleagues that have been recruited, and so on. Although my own research has had to take a back seat for much of the time, the discovery of the Higgs boson and the visit of Peter Higgs to the Department in 2012 were of great personal significance.

Finally, I am very grateful for the support, encouragement and wise advice of my senior management team. They regularly go beyond the call of duty on the Department's behalf, and deserve a large share of the credit for any success we have achieved. The Department is of course very fortunate to have Andy as its next Head. He has a wealth of experience as a member of the current management team, and will bring to the job new ideas and a fresh perspective. I wish him and the whole Department all the very best for the future.'

Andy Parker is Professor of High Energy Physics and, in addition to running that group, has been Deputy Head of Department for a number of years. In that role, he has taken particular responsibilities as Chair of the Finance Committee and a member of the Senior Management Group. He is therefore well aware of the challenges which lie ahead. In looking forward to taking on this new role, Andy said:

'*The Cavendish is performing some of the best research in the world, but it faces major challenges to preserve its pre-eminent position. Funding for all types of innovative research is becoming harder to find, particularly in the area of fundamental physics research which is more precarious than ever. We need to continue to attract the best talent in order to win the competitions in the UK and EU for major awards. This means that we need to provide state of the art facilities, and hence my first priority will be to continue the work of rebuilding the Laboratory. I will also be looking for opportunities to enhance collaborations inside the Cavendish, and with the rest of Cambridge, to capitalise on the strength in depth of the University and to national and international collaborations which are proving essential for many of our most ambitious projects.*

On the educational side, we can anticipate many changes to the school syllabus which will impact on our undergraduate courses. We also need to strengthen further the training and support for our graduate student community. We are now operating in a global market for University education, and our provision has to be world class.

It is a real honour to be asked to follow on from James and his illustrious predecessors. I expect that this will be a challenging, but also very rewarding, job. I am lucky to be supported by excellent staff at all levels, and I look forward to working closely with them to take the Laboratory forward.'

We all agree that James has done a superb job through what are always choppy waters and we owe him a great debt of gratitude for all his efforts. The winning of the Maxwell Centre is a fitting culmination of his period as Head of Department. Without the secure underpinning of the whole operation and the confidence the University has in the Department's academic distinction and effective management, such developments would not be possible. The transfer of responsibilities from James to Andy has every prospect of being as seamless as it could be, but of course every Head of Department puts his or her own stamp on the organisation. We all look forward to an exciting period of continuing evolution of the Department's vibrant programme under Andy's leadership.

Malcolm Longair

First Results from the Planck Cosmology Satellite


On 14th May 2009, the ESA Planck space telescope was launched from French Guiana on an Ariane 5 rocket (Fig. 1). Its mission was to map the Cosmic Microwave Background Radiation (CMB) in unprecedented detail over the whole sky. Mark Ashdown and Anthony Lasenby describe the work of the Cambridge astronomers, including members of the Cavendish Astrophysics group, who have been involved in the mission since its inception.

Fig. 1: The Planck and Herschel spacecraft were launched on an Ariane 5 rocket from French Guiana on 14th May 2009.

Planck has been more than 20 years in the making. The first proposals for a European CMB space mission were submitted to ESA in the early 1990s, after the successful detection of the anisotropies in the CMB by the NASA COBE spacecraft. Planck is the third-generation CMB space mission, the successor to COBE and another more recent NASA mission called WMAP.

The Planck spacecraft has a 1.5 metre telescope (Fig. 2). There are two instruments which use different technologies to detect microwave and sub-mm radiation. The Low Frequency Instrument (LFI) uses HEMT radio receivers and the High Frequency Instrument (HFI) uses bolometers. Between them the instruments are sensitive to nine frequency bands between 20 GHz and 1 THz. The instruments rely on a sophisticated cryogenic system to cool their detectors to the operating temperature. The HFI bolometers were cooled to 0.1 K using a helium dilution refrigerator, making them the coldest place in space.

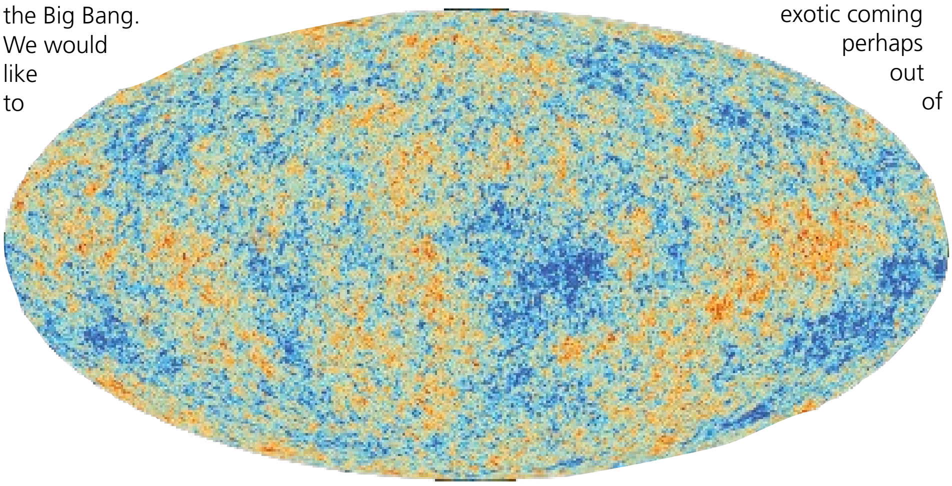
Planck is in orbit around the second Lagrange point of the Sun-Earth system, on the far side of the Earth from the Sun. The spacecraft spins on its axis to scan the sky, allowing it to cover the whole sky twice in one year. After the commissioning phase, the science survey started in August 2009.

The first cosmology results from Planck were published on 21st March 2013 as a set of 28 papers. At the same time, the data used to produce the results were made available for the public to download. The spectacular map of the CMB (Fig. 3) was produced by combining all nine maps from the frequency bands to remove foreground microwave emission from the Galaxy and extragalactic sources.

Fig. 2 An artist's impression of the Planck spacecraft.

So what is it that Planck is seeking to measure and what advances in our understanding of the Universe have these first results brought about? The key point is that the Cosmic Microwave Background is fossil radiation left over from the early Universe. On it, we can see imprinted the traces of structures which were present at a time about 350,000 years after the big bang, during an epoch called 'recombination', when the universe had cooled sufficiently for the matter to become neutral, so allowing the CMB photons to propagate towards us today. These structures, visible in the map of the CMB, have a twofold aspect. Firstly, they form the seeds of what later go on to form galaxies and clusters of galaxies and all the other structure we see around us today; secondly, they are themselves the imprint of what was generated at the very earliest times, during the epoch of inflation, which took place about 10^{-35} seconds after the Big Bang. We would like to understand and have pointers to the physics of inflation, which happens at energies probably about 10^{12} times greater than the largest accessible at CERN, and therefore well into the realms of 'new physics', or physics beyond any energy frontier that we are ever likely to encounter here on Earth. Early thoughts about this period of inflation, back in the early 80s, led to ideas that we are now able to start testing today - Planck has the precision to do this which no previous experiment has had.

As an example, a main prediction of inflation is that the fluctuation power, which is generated by Heisenberg-uncertainty type fluctuations in whatever field was around at that time should not be precisely the same on all scales, which had been generically assumed by the original theories - these fields might be a simple scalar field though probably something more exotic coming perhaps out of



string theory. Instead there should be larger ripples on larger scales - this has now finally been categorically demonstrated by Planck, using one of Planck's main results - the 'power spectrum' of the CMB fluctuations shown in Fig. 4.

The solid line shows the predictions from a simple cosmological model, called the Lambda CDM model, in which the main constituents of the Universe's energy budget are 'Dark Energy' in the form of a cosmological constant, Dark Matter, and ordinary baryons from which we and everything else we can see are made, but the latter accounting for less than 5% of the total. The curve may appear complicated, but this is due to reprocessing during the later recombination period of the primordial spectrum produced by inflation. Working back using the known physics of recombination, the results show that the underlying spectrum of perturbations has the form and slope predicted by inflation.

Fig. 3. Left: The cosmic microwave background as seen by Planck. This image shows the primordial fluctuations in the CMB, which have an amplitude of a few times 10^{-5} of the mean temperature of 3K.

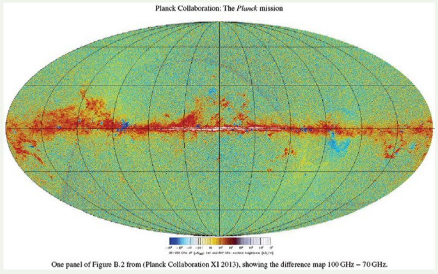
Fig. 4. Right: The power spectrum of temperature fluctuations in the cosmic microwave background as measured by Planck. The red points with error bars are the Planck measurements. The green line is the prediction from the best-fit 6-parameter cosmological model, which includes a cosmological constant and cold dark matter.

The thought that these predictions relating to this incredibly early period were made 30 years ago and have now been demonstrated by experiment, is quite remarkable, and gives us the brightest hope yet for discovering new physics via cosmology.

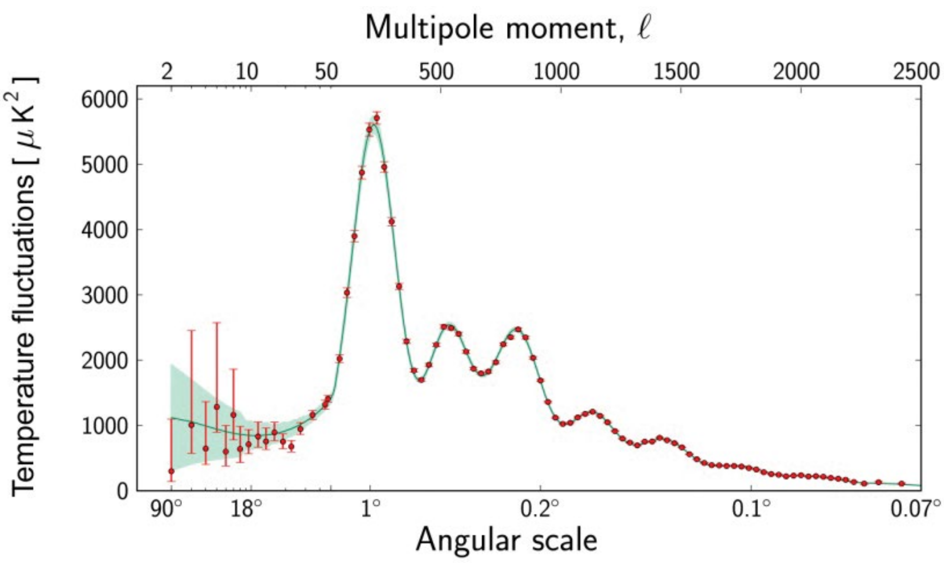
Planck has also significantly refined our picture of the parameters of the cosmos. We now know that the Universe is flat to much higher precision than we knew before, to almost 1 part in 1000 - this again is a generic prediction of inflation. Just think of blowing up a balloon by 10^{25} times or so and it will tend to make the surface appear flat! Planck has also refined our estimates of the age and composition of the cosmos, and in particular the Planck data require us to accept both Dark Energy and Dark Matter independently of any other experiments - again a great step forward. However, although the fit of the data to the simple 6-parameter Lambda CDM model is very good, at the same time, the picture of the Universe on the largest scales revealed by Planck has some mysteries - why does one part of the sky appear to have more fluctuations in it than the other half, why is there less power than we'd expect on large scales, why is there evidence for some sort of cosmic rotation being visible when the necessary parameters do not accurately match the other parameters we have measured?

The helium needed to cool the HFI detectors was exhausted in January 2012. The LFI will be turned off later this year and Planck will be ejected from its orbit around L2 shortly afterwards. But, this is not the end of the story. Less than half of the data were used to produce the results released this year. The final release including data on CMB polarisation are scheduled to be released in mid-2014, and will be vital in helping to answer these and other deep questions to which we currently do not have answers, even given the huge step forward which the current data has achieved.

Dr Mark Ashdown is a Senior Research Associate and Manager of the Cambridge Planck Analysis Centre, and Anthony Lasenby is Professor of Astrophysics and Cosmology at the Cavendish, and Acting Director of the Kavli Institute for Cosmology.



Some measure of the remarkable quality of the Planck data is provided by the above difference map between the images of the sky made independently by the HFI instrument at 100 GHZ and the LFI instrument at 70 GHz. The HFI and LFI teams used their own independent software packages to create 'cleaned' maps of the CMB sky. The residual signals in the Galactic Plane are due to the presence of the emission line carbon monoxide in the higher frequency channel. The faint arc is due to a strip of enhanced noise in one of the strip scan regions. The signals away from these regions are pure random noise, showing that, despite the very different approaches, both instruments have performed exactly to their design specifications. We can have confidence that Fig. 3 is a very accurate image of the CMB.



Quantum Sensor Technology for Observational Astrophysics

Over the last thirty years, superconducting quantum sensor technology has played a major role in realising advanced programmes in observational astrophysics, writes Stafford Withington. All existing and planned ground-based and space-borne millimetre-wave, submillimetre-wave and far-infrared astronomical observatories[1] are completely reliant on superconducting imaging technology of one kind or another. Without superconducting sensors, major ground-based observatories such the JCMT, CSO, APEX, IRAM, ALMA, ASTE, and SPT would not exist, and space-borne observatories such as Herschel-HIFI[2] would not have been possible.

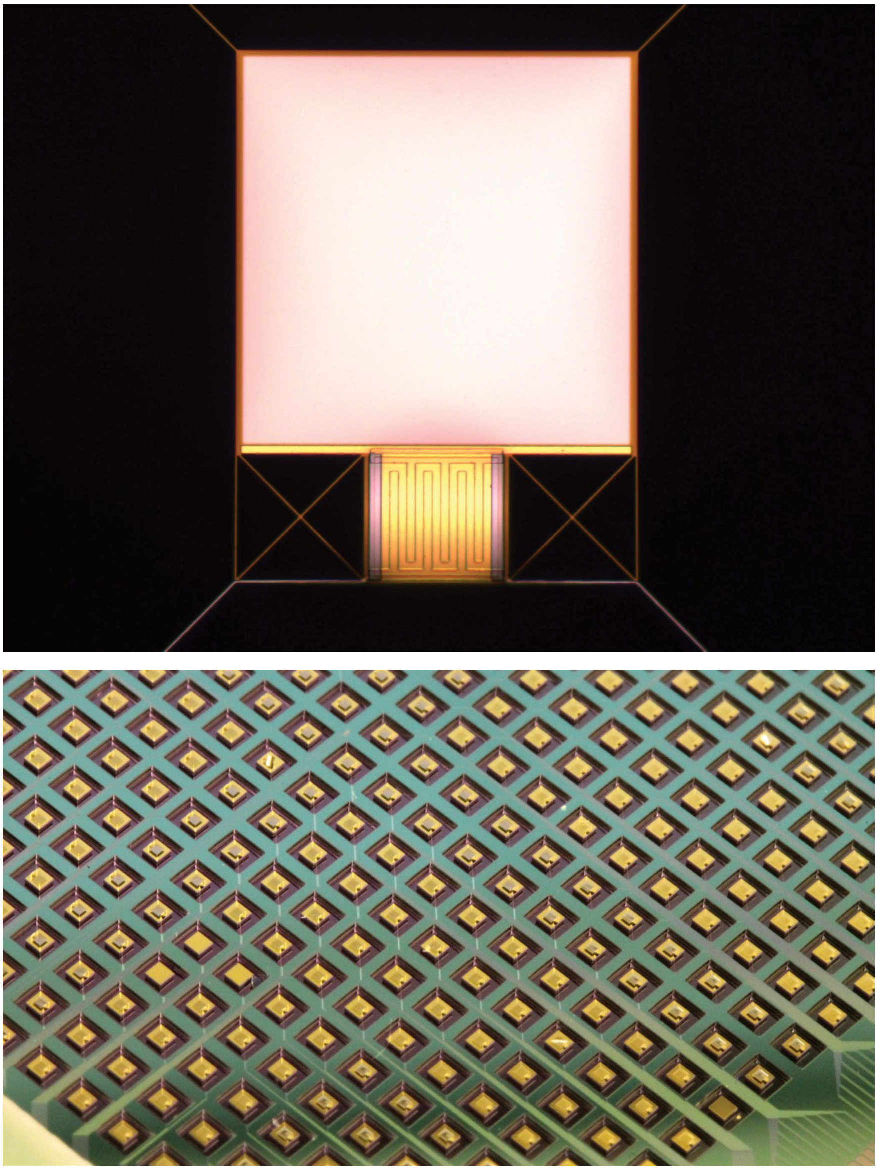


Fig. 1: A 110-220µm MoAu TES imaging array developed for the JAXA/ESA cooled aperture space telescope SPICA. The individual pixels are fabricated on 200 nm SiN membranes (top) and packed into large fully superconducting micro-machined Si arrays (bottom). The array is cooled to 70 mK and read out using integrated SQUIDs. This array is one of the most sensitive FIR imaging arrays ever built. Each of its 388 pixels can detect a 100W light bulb being turned on and off in 1s at a distance of 7 million miles.

Looking to the future, many international astronomical projects are critically dependent on superconducting sensors. These include ground based telescopes such as CCAT[3] in Chile and the GLT at Summit Station[4] in Greenland, the Italian Space Agency's long-duration circumpolar balloon experiment LPSE[5], the Japanese/European Space Agencies' SPICA mission[6] to place a cooled-aperture (3.5K) FIR space telescope at the L2 Lagrangian point, the proposed Planck follow-on mission PRISM[7] and the long-term ambition to place a far-infrared interferometer in space, FIRI[8]. In addition, time-resolved photon-counting hyper-spectral imaging arrays are being developed for optical and ultraviolet astronomy, and any future X-ray telescope will be dependent on fast superconducting calorimeters. Thus, superconducting quantum sensor technology is completely dominant in astronomy, and the situation will not change for several decades to come.

Despite the pivotal importance of this technology, very few laboratories around the world are capable of developing the complex, high-performance, science-grade components needed. The Detector Physics Group at the Cavendish Laboratory runs a state-of-the-art facility for manufacturing and testing superconducting microcircuits for the applied sciences. The facility was established over ten years ago and since that time has become a world leader in the development of ultra-low-noise quantum sensors, quantum mixers, and imaging arrays. The Group has expertise in manufacturing multi-layer thin-film devices using a wide variety of materials, (bcc)Ta, β-Ta, NbN, Nb, Al, Mo, Hf, Ir, Au, Cu, SiO, SiO_2, whose properties are known and controlled precisely. The Group regularly makes complex multi-layer components on 4″ wafers, micromachined Si and SiN membranes, as well as Si, quartz, and Sapphire substrates.

Superconducting sensors are unique in providing background-limited photometric and spectroscopic capabilities at the world's best high-altitude observing sites, and in space. At the present time there are five generic device types, around which all instruments are based:

- Transition Edge Sensors (TESs), which use membrane-suspended superconducting bilayers to produce extraordinarily sensitive bolometers;
- Kinetic Inductance Detectors (KIDs), which use the kinetic inductance effect in a thin-film resonator to produce large arrays of detectors that can be read out using a single transmission line, fast digital electronics, and Software Defined Radio;
- Cold Electron Bolometers (CEBs), which are similar to TESs, but which do not rely on the generation of an excess population of non-equilibrium quasiparticles, but which use an intrinsic solid-state refrigeration mechanism to cool the active volume below the bath temperature;
- Superconductor-Insulator-Superconducting (SIS) mixers, which use quasiparticle tunneling to produce quantum-limited mixing with near ideal

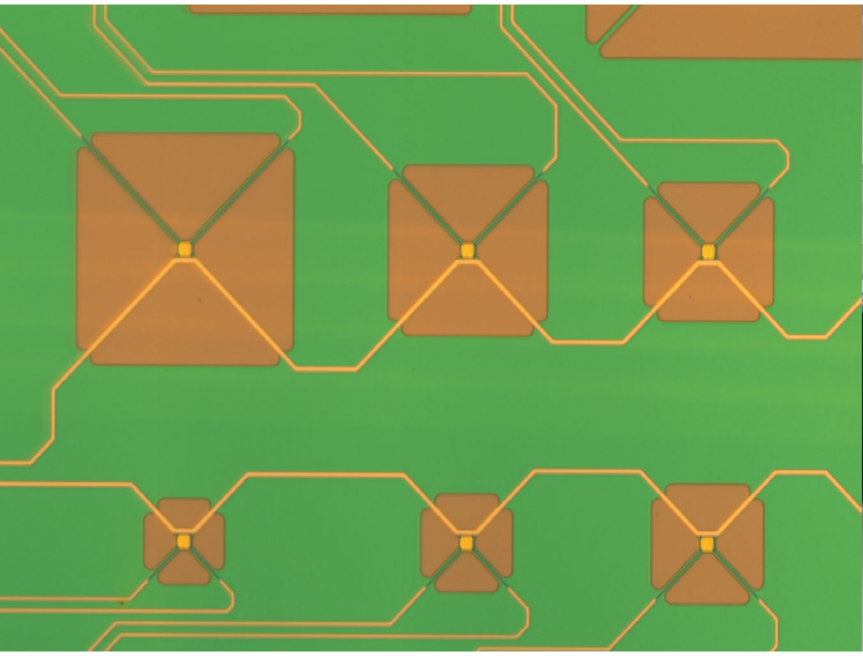


Fig. 2: An array of microcalorimeters. Each device comprises a TES on a 200 nm suspended SiN membrane. A single superconducting RF transmission line meanders over the chip, along the legs, for the purpose of controlling thermal conductance using a microwave signal. This chip is being used to study phonon scattering by Two Level Systems in the highly amorphous SiN dielectric.

Fig. 3: Ultra High Vacuum (<10^{-10} Torr) thin-film sputtering facilities used for manufacturing superconducting microcircuits using (bcc)Ta, β-Ta, NbN, Nb, Al, Mo, Hf, Ir, Au, Cu, SiO, SiO_2.

characteristics from 100 GHz to 1.2 THz;

- Hot Electron Bolometers (HEBs), which use the nonlinearities of superconducting microbridges to achieve low noise mixing from 1 THz to 6 THz.

Superconducting Tunnel Junctions (STJs) are also used for optical photon counting, and TESs are used for time-resolved photon counting spectroscopy at X-ray wavelengths. KIDs can be engineered in many different ways to operate over the whole of the electromagnetic spectrum, and they are being developed intensively for a wide variety of applications. In the context of low-noise electronics, large-format arrays of SQUIDs are used to readout TESs, and the recent invention of a superconducting thin-film parametric amplifier is likely to replace HEMT amplifiers.

The exploration of quantum sensor physics and the development of quantum sensor technology are intellectually rich in their own right, and require the study of many underlying physical processes in order to be able to make progress, and to control all of the various noise mechanisms. For example, we have a programme to study heat transport and thermal fluctuation noise in patterned low-dimensional (200 x 700 x 1000 nm) dielectric microbridges for the purpose of developing phononic filters. It should also be appreciated that modern detector technology has moved well beyond merely fabricated individual devices, and now complex microcircuits are produced having thousands of devices working at THz frequencies. The trend is towards high levels of on-chip functionality, and to read out these chips using fast digital electronics and Software Defined Radio.

Currently we are working on a chip spectrometer for the new submillimetre-wave Greenland Telescope, which will be placed at Summit Station in the centre of the Greenland ice sheet at an altitude of 3211 m. Working with the Harvard Smithsonian Center for Astrophysics (CFA), our vision is to create a sensitive FIR imaging technology where each detector in a focal-plane is intrinsically capable of yielding detailed spectroscopic information. Each pixel will have hundreds of spectroscopic channels, all read out using fast digital signal processing techniques. Medium spectral-resolution channels ($R=\Delta\lambda/\lambda\sim500$-$1000$) will be used for wide-field blind surveys of high-redshift single or multiple spectral-lines, and high spectral-resolution channels ($R=\Delta\lambda/\lambda\sim2000$-$4000$) will be used for multiline mapping of molecular outflows in star-forming regions and extended nearby galaxies.

In the area of quantum sensor technology, the Detector Physics Group has formal research programmes with a number of international organisations: the Space Research Organisation of the Netherlands (SRON), the European Space Agency (ESA), the European Southern Observatory (ESO), the Goddard Space Flight Center Washington (GSFC), the National Standards Agency of Germany, the Physikalisch-Technische Bundesanstalt (PTB), the National Physical Laboratory UK (NPL), and the South West Research Institute Texas (SWRI). Some of these activities relate to astronomy, but others are aimed at developing quantum sensor technology and measurement techniques for non-astronomical applications. Not only is superconducting sensor technology of crucial importance to astronomy, it also has considerable significance in other areas. For example, our modelling of non-equilibrium quasiparticle-phonon dynamics in thin films, and our ability to fabricate tunnel-junctions combined with high-Q thin-film resonators are closely related to studies being undertaken by quantum information groups aiming to realise qubits for quantum computing[9]. Our work is also closely related to extensive programmes being carried out on the realisation of a standard for the quantum candela[10].

Stafford Withington

Stafford Withington is Professor in Analytical Physics and Head of the Detector Physics Group, soon to be renamed the ***Quantum Sensors and Measurements Group****.*

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1. The observatories operate in the 3 mm – 10 μm, 100 GHz – 30 THz wavebands
2. www.esa.int/Our_Activities/Space_Science/Herschel_overview
3. www.ccatobservatory.org
4. www.summitcamp.org
5. www.rssd.esa.int/SA/PLANCK/docs/eslab47/Session10_Experimental_Aspects/47ESLAB_April_04_12_30_Piacentini.pdf
6. http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42281
7. www.prism-mission.org
8. http://arxiv.org/ftp/arxiv/papers/0707/0707.1822.pdf
9. http://arxiv.org/abs/cond-mat/0411174
10. www.quantumcandela.net

Fulfilling Maxwell's Vision for Hands-on Experimental Physics

In CavMag5, we reported a new programme of workshop training for graduate students under the supervision of Nigel Palfrey. This has proved to be an enormous success, eighty-eight students now having passed through the one-week training course in groups of up to four students at a time.

As I probe more deeply into the early history of the Laboratory, James Clerk Maxwell's vision of the key role of hands-on skills in experimental physics was at the very heart of the Laboratory's rapid growth to prominence in the latter years of the 19th century. In characteristic fashion, Maxwell delivered his inaugural lecture entitled *Introductory Lecture on Experimental Physics*, not in the Senate House, but in an obscure lecture room and without much publicity on 25 October 1871. There was at best a modest audience, but what he said was deep, far-reaching and set the tone for what he hoped the Laboratory would achieve. From the outset, Maxwell's aim was to create a world-leading laboratory for experimental physics from scratch. He set out the goals of the Laboratory, contrasting the emphasis upon mathematics in the Tripos with the importance of developing precise experimental technique. In his words,

'When we shall be able to employ in scientific education, not only the trained attention of the student, and his familiarity with symbols, but the keenness of his eye, the quickness of his ear, the delicacy of his touch, and the adroitness of his fingers, we shall not only extend our influence over a class of men who are not fond of cold abstractions, but, by opening at once all the gateways of knowledge, we shall ensure the association of the doctrines of science with those elementary sensations which form the obscure background of all our conscious thoughts, and which lend a vividness and relief to ideas, which, when presented as mere abstract terms, are apt to fade entirely from the memory.'

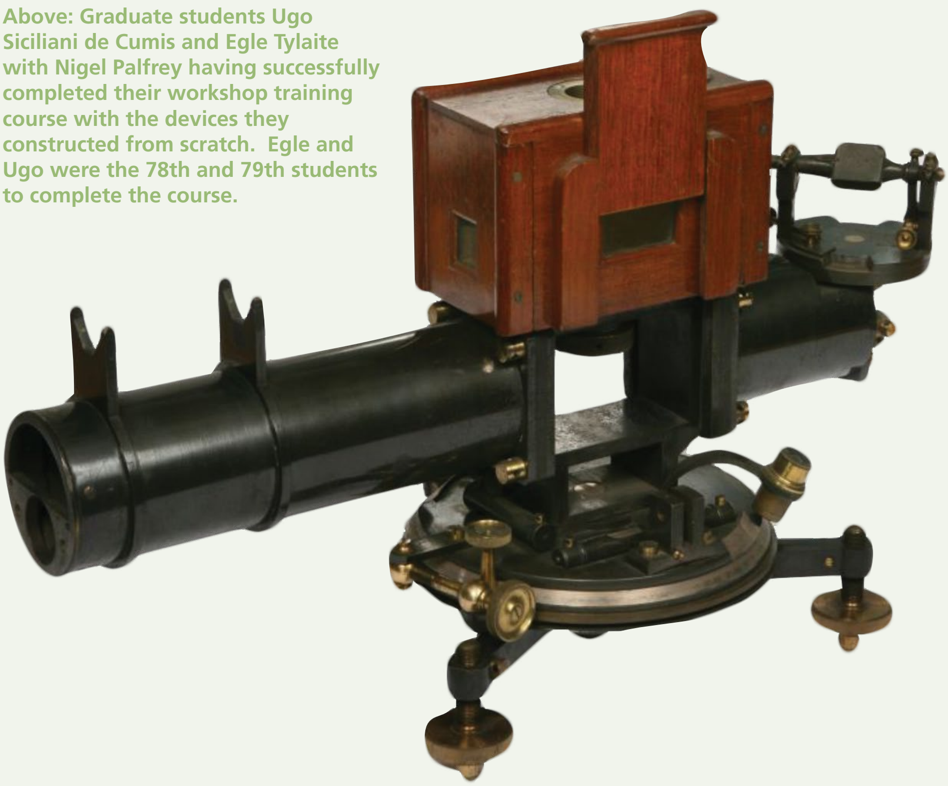
Above: Graduate students Ugo Siciliani de Cumis and Egle Tylaite with Nigel Palfrey having successfully completed their workshop training course with the devices they constructed from scratch. Egle and Ugo were the 78th and 79th students to complete the course.

As part of the training programme in precise experimental technique, Maxwell purchased the Kew magnetometer for £60. Jim Bennett and his colleagues[1] have written about this experiment:

'The Kew Magnetometer was a good way of starting. Using the instrument to measure the Earth's magnetic field provided the student with valuable training in the careful reading of scales and the difficulties of time measurement of the oscillating magnet. Levelling the instrument and isolating it from extraneous magnetic fields already taught important lessons about the special requirements of exact physical measurement. If the student needed help, he sought out the demonstrator William Garnett, who could explain the techniques involved.'

But it was a tricky experiment. Maxwell devoted Chapter 7, pages 95 to 128, of Volume 2 of his great *Treatise on Electricity and Magnetism* to its principles of operation, including all the higher order corrections he expected the student to understand. In A.P. Trotter's *Elementary Science at Cambridge, 1876—1879*, he wrote:

'The instrument, though formidable in appearance, seemed easy to understand. The method of counting swings was novel and interesting, but I ran up against



the 'moment' of the magnet, an abstraction to which I had not been introduced. I appealed to Garnett … Garnett tried to show me how the moment of variously shaped bodies was calculated. I could not take this in because I had read nothing of differential or integral calculus … My ignorance did not prevent the production of fairly good results.'

Thus, the key role of hands-on experimentation was built into the fabric of the Laboratory from the very beginning. The present workshop training course is the natural contemporary extension of the tradition and it has proved to be very popular and rewarding for the graduate students. Nigel has now supervised the training of 88 students since the course began a couple of years ago. Gratifyingly, the number of female graduate students is 22, roughly the same fraction of female graduate students in the Laboratory as a whole. This is a far cry from the 1930s when Mrs. Constable (Miss Sparshott) recalled that she and Helen McGaw were forbidden to take part in a workshop training course (see CavMag3).

As Nigel wrote to Egle and Ugo after the course,

'Well done on completing the 'challenging' training project. Do hope you are pleased with what you have learnt and achieved in such a short space of time over the last few days ... and thank you very much for the hand baked cake you kindly made for me, much enjoyed and much appreciated!'

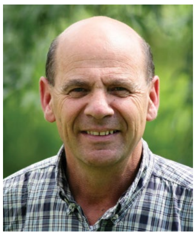
The training programme is not standing still, but is now being extended to Computer Aided Design (CAD) techniques and in due course to Electronics as well.

Malcolm Longair

1. Bennett *et al*. 1993. *Empires of Physics: A Guide to the Exhibition*, Cambridge: Whipple Museum of the History of Science.

Left: The Kew magnetometer which was used as a training exercise in experimental physics. It is now in the Laboratory's exhibition of experimental apparatus purchased by Maxwell for the practical education of students.

Rutherford Schools Physics Project Launched



A new five-year project aimed at developing the skills of sixth-form physicists has been awarded a £7 million grant by the Department for Education.

The Rutherford Schools Physics Project, led by Mark Warner and Lisa Jardine-Wright, will work collaboratively with teachers, schools and other partner universities to deliver extension materials, on-line learning, workshops for students and support for physics teachers. The Department for Education has agreed to support the project with a £7 million grant over five and a half years.

Mark and Lisa have been running the very successful Senior Physics Challenge for many years and the new programme offers the opportunity to extend the inspiration of that course to school pupils throughout the country. Lisa has also been spearheading our outreach efforts as our Schools Liaison Officer with outstanding success. We congratulate them both on this very significant achievement.

It is simplest to allow Mark to describe the vision in his own words:

"Since Archimedes, mathematics and physics have been inseparable, and the inter-dependence continues into the 21st century. Applications of physics, as well as engineering, biology and chemistry, have transformed the world. Physics both underpins these related disciplines and makes fundamental advances in our understanding of our world. This mathematical basis and the excitement of focussing on problem solving are the driving forces behind the Rutherford Schools Physics Project.

"University physics is ideally suited to students who are fluent in mathematics and have an appetite for problem-solving. Universities want to admit students who are beginning to demonstrate that they think like physicists. This includes skills such as sketching diagrams to assess a problem, deconstructing problems, sifting information, assembling ideas from different areas of physics, and using their mathematical skills.

"The Rutherford Schools Physics Project will provide extension materials for students and support for teachers in developing these key skills and methods, working within the framework of the existing A-level curriculum."

The learning resources and activities offered by the project will enable more students from all backgrounds to gain physics expertise beyond school level, encourage more students to apply for physics, engineering and mathematics at universities throughout the UK, and equip them to best demonstrate their academic potential. The grant will allow the project to deliver a mix of online learning, independent study, and work in schools with teachers. Cambridge computer science experts will develop an online delivery platform inspired by the successful use of MOOCs in the USA.

The Rutherford School Physics Project will develop its resources in close collaboration with teachers and schools. Experienced physics teachers will lead continued professional development sessions and master-classes, while the Project will work in close partnership with schools interested in teaching their own students and those from surrounding schools on a regular basis. This may include schools with less experience of supporting students into Physics at university.

James Stirling, Head of the Cavendish Laboratory, said:

"The Cavendish has a longstanding tradition of recruiting, training and inspiring physics students. Working closely with school students and their teachers has become an increasingly important part of this. The Rutherford Schools Physics Project will add tremendous value to this work, and I am delighted that the Department is playing a leading role."

The project will also work closely with its two sister initiatives, the Cambridge Mathematics Education Project, led by Professor Martin Hyland and also supported by the Department for Education, and "i-want-to-study-engineering.org", led by Professor Richard Prager and supported by the Underwood Trust.

Secretary of State Michael Gove said:

"Professor Warner's brilliant project will give state school pupils access to advanced materials so they can develop problem-solving skills in maths and physics. Cambridge University physicists will provide support for science teachers and online resources enabling many more state school students to succeed at university."

Outreach: Summer and Autumn update 2013

New Initiative

Cambridge Colleges' Physics Experience
In 2012 the Laboratory made a successful bid for funds to begin a new 3 year initiative to collaborate with the Cambridge Colleges to reach areas of the UK currently with low participation in University of Cambridge admissions. The CCPE programme draws together two existing successful schemes, the Cavendish School Workshops[1] and the University's area link scheme[2] to provide a one-day visit for schools. Through the new programme we aim to**:**

1. Change perceptions and stereotypes of Physics and Cambridge University.
2. Increase take up in physics at A-level amongst students in schools where current numbers are identified as exceptionally low.
3. Raise awareness, achievement and increase participation in physics for 13-17 year olds at the next stage of their career, GCSE, A-Level and University.
4. Provide role models, support, motivation and experience to promote 'girls into physics' with specific reference to applications to Cambridge.

The programme is timetabled to target specifically students at transition stages in their education:

- year 9 students before option choices are made for GCSE
- year 11 before A-level choices are made
- year 12, when students are thinking about university choices

We have successfully run 4 events this year in collaboration with this year's college partners, Clare, Christ's, Pembroke, St Catherines and Newnham. In October 2012 we hosted 120 year 11 students, in February 2013, 180 year 12 students and in May 2013, 200 year 9 students. In the Easter Holidays we hosted a girls only event for 30, Y12 students in collaboration with Newnham College.

In the next academic year, having piloted our infrastructure and schedule, we hope that we will be joined in collaboration by a number of other colleges to extend our reach, particularly into the North East of England.

Regulars Events

Physics Teachers' Cambridge Residential 2013
From the 29th June to 1st July, 28 A-level physics teachers from across the United Kingdom visited Cambridge for a residential workshop kindly hosted by Robinson College and sponsored by the Ogden Trust. The objectives were described in CavMag9[3], to which reference should be made for further details. This is now the third year of this initiative and through the new Rutherford project we hope that it will be expanded to include more of these residentials throughout the academic year. For more information please see our website[4].

Senior Physics Challenge
We received nearly 300 applications from the highest calibre Y12 (AS-level) students to participate in our physics access and admissions initiative called the Senior Physics Challenge. From these 66 students were selected to visit Cambridge this summer, each from different schools located all over the United Kingdom.

The summer school took place over four nights from the 30th June until the 4th July during which the students attended lectures on kinematics and special relativity and practical laboratory classes on dynamics and optics. Time was also given for students to attend admissions talks and generally discuss physics and socialise with like-minded students of a similar age. The aim of these four days of intensive tuition is to develop problem-solving and experimental skills and to demystify the transition from A-level (or equivalent) to university physics.

Each year participants are kindly hosted to dinner and accommodated by a number of Cambridge colleges. Participating colleges in 2013 include Christ's, Churchill, Corpus Christi, Fitzwilliam, Newnham, Pembroke, Peterhouse, Robinson, St John's and Trinity.

Student application is initiated by teacher recommendation and whilst selection for 2013 is complete any interested teacher may register online to receive updates and notification of the next application round. To find out more please see our website[5].

Undergraduate Open Days

From 2:00 pm on the 4th and 5th of July the Cavendish Laboratory opened its doors to the next wave of potential undergraduates. These open afternoons are designed to coincide with the Cambridge University central admissions open days, but are stand alone activities to which any year twelve (AS-level or equivalent) students and their family are invited to attend.

There is no need to register or book for these open afternoons but further information can be found on our website[6].

Physics at Work 2013 – Bookings now open

Bookings for the 29th annual *Physics at Work* exhibition are now open to schools – and spaces are filling up fast! This unique exhibition runs for three days, this year from 24th until 26th September 2013, with two sessions each day (morning sessions begin at 9am and afternoon sessions at 1pm). During each half day session school groups will see six different exhibits selected by the organisers to include both internal and industrial exhibitors and to show the many varied ways in which physics is used in the real world. We are delighted to welcome both seasoned and new exhibitors to the event once again this year, bringing our total number of exhibits for 2013 to twenty-five.

The exhibition is targeted at 14 -16 year olds with some schools bringing their *gifted and talented* year 9 students and others bringing year 12 students who are considering potential careers in physics. Schools are welcome to bring as many students as they are able, given a teacher to student ratio of about 1 to 15. On arrival at the Cavendish, a given school party will be split into groups of approximately 15 students with 1 accompany teacher. Map in hand each group is then led to their first exhibit to follow their own tailored route around the Cavendish.

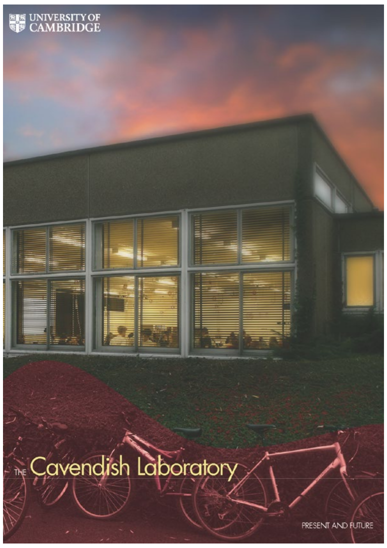
Approximately 400 FREE places are available for each half day session and schools travel from all over London and the South East to attend this event. Any teachers interested in attending the 2013 exhibition should book online as soon as possible to avoid disappointment at

www-outreach.phy.cam.ac.uk/physics_at_work.

Lisa Jardine-Wright

1. www-outreach.phy.cam.ac.uk/workshop
2. www.study.cam.ac.uk/undergraduate/access/arealinks
3. www.phy.cam.ac.uk/alumni/alumnifiles/CavMag_9.pdf
4. www-outreach.phy.cam.ac.uk/Teacher-Res
5. www-spc.phy.cam.ac.uk
6. www-outreach.phy.cam.ac.uk/uopenday

New Cavendish Brochure



It is only five years since the last edition of the Cavendish Brochure was published and yet, looking at it today, it reads like a tale from a different world and a different epoch. The pace of change in all areas of the physical sciences has been dramatic with many new areas, which were only a gleam in the eye, now being parts of the core of the Cavendish's research activities.

At the same time, despite the well-rehearsed problems of funding and the introduction of student fees, the Cavendish has continued to expand the scope of its activities in research and teaching. There are now well over 900 persons in the Laboratory, comprising academic staff, post-doctoral scientists, support staff and graduate students. In addition, teaching is provided for about 860 undergraduates through the four years of the physics course. It remains a real challenge to maintain freshness and originality with such large numbers of persons on site, but everyone has risen to the challenge with enthusiasm and all aspects of the programme are in a vibrant state of good health.

It is impossible to describe everything that is going on in the Laboratory and so we have adopted a slightly different approach in this edition of the brochure. We need to include factual information about the Laboratory, but at the core of the brochure has to be the physics and the frontier research challenges which are facing our colleagues. So, we have adopted the approach of describing the 'top-level' activities of our research groups in the various 'Universes' – for convenience, we divide the research activities into the Extreme, Biological, Quantum and Materials Universes. Recent highlights of the cutting edge research being carried out in each 'Universe' appear regularly in *CavMag*[1], our Alumni magazine.

We emphasise that these are but the tip of the iceberg of the excellent science being carried out in the Laboratory. For many more details of all the research being carried out in the Laboratory, reference should be made to the web-sites of the individual research groups. Their web-addresses are given on the summary pages and we strongly urge readers to follow up their interests on these pages.

In addition to the research and teaching programmes, which remain the heart of our activities, we draw special attention to the other aspects of our work which play a prominent role in the life of the Laboratory – these include our interactions with industry, our outreach programmes to young people and our plans for redevelopment of the Laboratory.

We hope you will enjoy this snapshot of the Cavendish. We will greatly value your feedback and comments about this endeavour.

The new edition of the brochure can be found at:

www.phy.cam.ac.uk/alumni/alumnifiles/Physics_Brochure_2013.pdf

If you would like a hard copy of the brochure, do not hesitate to contact us either at

lh294@cam.ac.uk or **development@phy.cam.ac.uk**

or by post to the Laboratory address on the back cover of this edition of *CavMag*.

Malcolm Longair

1. All editions of CavMag can be view on line at: www.phy.cam.ac.uk/alumni

IOP | Institute of Physics
Juno Champion

IOP Juno Champion status renewed for a further three years

Project Juno recognises and rewards the progress that physics departments are making to address the under-representation of women at all levels in university physics. The Department's Juno Champion status is the highest level of attainment within the scheme. In renewing the Laboratory's Champion status for a further three years, the Juno assessment panel commented:

"We were very impressed by efforts within the department on outreach activities, which benefits the whole physics community, and the efforts to promote promotions to senior levels, which appears to be particularly benefiting female colleagues. We were also pleased to see the extensive use of exit interviews and the way information from these was being used to improve practice. All of this points to a real commitment to the dissemination of best practice within your institution, as well as the community as a whole."

Congratulations to everyone who has contributed to this important achievement, especially to **Val Gibson** and **David Peet**, who masterminded this activity on behalf of the Department.

Cavendish ranked second physics department in the world in the 2013 QS World University Rankings

We are delighted to report that the 2013 QS World University Rankings has placed the Cavendish Laboratory second in the world. For reference the top ten physics and astronomy departments in rank order were:

1. Massachusetts Institute of Technology (MIT)
2. **University of Cambridge**
3. Harvard University
4. Stanford University
5. University of California, Berkeley (UCB)
6. University of Oxford
7. Princeton University
8. California Institute of Technology (Caltech)
9. The University of Tokyo
10. ETH Zurich (Swiss Federal Institute of Technology)

Suchitra Sebastian awarded an ERC Starting Grant

Royal Society URF Suchitra Sebastian has been awarded a prestigious five year Starting Grant by the European Research Council (ERC) for her research project titled '*Unconventional Superconductivity from a Mott Insulating Parent Material*'.

She has also been awarded a UK and Ireland L'Oréal UNESCO For Women in Science Fellowship

Richard Friend has continued to harvest prestigious awards:

i. Foreign Member of the US National Academy of Engineering
ii. International Medal for Materials Science and Technology, Materials Research Society of India
iii. Honorary Degree, University of Hasselt (Belgium)

Promotions

Congratulations to **Chris Ford** (left) of the Semiconductor Physics Group on his promotion to a Professorship and to **Pietro Cicuta** (lower left) and **Ulrich Keyser** (lower right), both of the Biological and Soft Systems Sector, on their promotions to Readerships with effect from 1st October 2013.

Departure of Michael Koehl and David MacKay

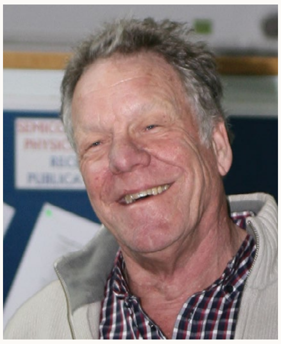
Two of our Professors, **Michael Koehl** and **David MacKay**, left the Department earlier this year. Michael has been appointed as Professor of Physics at the University of Bonn. David has been appointed Regius Professor in Engineering in the Department of Engineering here in Cambridge. We thank both Michael and David for their outstanding contributions to the Cavendish. We are sad to see them go, but wish them all success and look forward to keeping in contact with them in their new positions.

Keith Matthews completes thirty-five years in the Cavendish

Keith Matthews, the Head of Maintenance, completed 35 years of service with the Laboratory this year. Keith is shown opposite with Administrative Secretary David Peat (left), Head of Department James Stirling (second from right), and Laboratory Superintendent Peter Norman (far right). In the foreground is the garden furniture, selected by Keith, which was presented to him in recognition of his sterling service to the Department.

Athene Donald has been awarded Honorary Fellowship of the Institute of Physics. She is also one of 12 leading female scientists awarded Suffrage Heirloom Jewellery and Textiles. These items commemorate suffragette leader Emmeline Pankhurst, whose great-granddaughter Helen and her daughter Laura presented Athene and the other recipients with bespoke heirloom textiles in the form of bracelets. They also receive bespoke heirloom jewellery, a gesture harking back to days when handcrafted jewellery was presented to noted women of the suffrage movement.

Jeremy Baumberg, Head of the Nanophotonics Research Group, has been awarded The Institute of Physics Young Medal and prize. It is awarded in odd numbered years in memory of Thomas Young for distinguished research in the field of optics, including physics outside the visible region.



Doug Heftel Retirement

Doug has been a key contributor to the Semiconductor Physics Group since he joined in 1986. He has done many different things since that time, including building clean-rooms and MBE laboratories, electronic apparatus and maintaining the MBE UV facilities. He will be sadly missed, but we wish him the best of health and happiness for the future.

Head of Finance

We are delighted to welcome **Emily Challis** as Finance Manager for the Department. She comes to the Cavendish from the Finance Division of the University where she was involved in Financial Planning and Analysis.

Arrivals

We also welcome:

Linda Whyles, Group Administrator for Thin Film Magnetism and Surface, Microstructure and Fracture Groups.
Maciej Florczyk as Kitchen Porter in the common room.

Calling all alumni: the Alumni Festival 2013

During the Alumni Festival this year (27–29 September), your editor will be delivering a lecture on a new approach to the history of the Cavendish Laboratory. It will be followed by a unique opportunity to sample the exhibition "Physics at Work", which is described on page 17. Here is what is written in the Alumni Festival prospectus.

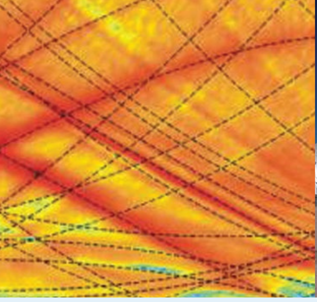
***Event Description -** Professor Malcolm Longair, Emeritus Jacksonian Professor of Natural Philosophy and former Head of the Cavendish Laboratory, explores "A New History of the Cavendish Laboratory - What Really Happened"; followed by "Physics at Work", an exhibition presented by those at the cutting-edge of research and development showcasing the many uses of physics in everyday life, along with applications of physics in research and industry.*

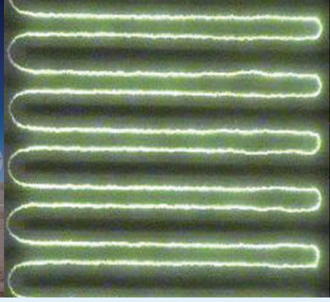
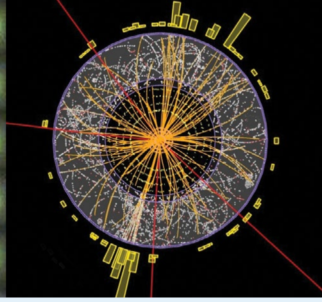
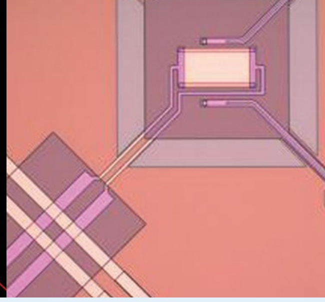
Refreshments available between 3pm and 4pm.

Meeting Point - Entrance Foyer, Pippard Lecture Theatre, Bragg Building,Cavendish Laboratory

Date: Friday 27 September 2013 **Time:** 2:00 PM to 5:00 PM
Location: Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE

We look forward to welcoming as many of you as can make the event. Please see **alumni.cam.ac.uk/festival13** for how to book



Afterword - CavMag10, really?

Can this really be the tenth edition of *CavMag*? When we sent out *CavMag1* five years ago as part of our initiative to reconnect with Physics Alumni and colleagues across the globe (and within the Laboratory, dare I say), I had no idea how quickly *CavMag* would become part of the furniture of the Laboratory. The idea of communicating the wonderful new science and all the other activities going on in the Laboratory through *CavMag* is now just part of life and it is having an impact far beyond my ambitions when we started. I am very grateful to readers for their complimentary letters and e-mails and for the generous words from my colleagues in the Department.

One of the bonuses, which I had not anticipated when we started out, is that we are creating an accessible record of the huge range of activity in the Laboratory, which will act as a historical record and a source of information for future historians of science.

Thanks are due to the many people who have contributed to the effort. First of all, there are my colleagues in the Cavendish who have generously provided excellent articles about the physics and other activities going on in the Department. I am delighted that no-one has yet said "No", but of course there is always a first time.

But, most important, very warm thanks go to many people 'behind the scenes'. Over the last five years, we have had a number of very significant successes in the Cavendish Development programme – the Winton programme, the Battcock Centre for Experimental Astrophysics and now the Maxwell Centre, to mention only three of the highlights. None of these successes nor *CavMag* would have been possible without our very effective and mutually supportive collaboration with the Cambridge University Development Office (CUDO). It is not possible to list all those who have been so helpful, but mention must be made of the associate Directors of the CUDO with whom it is such a pleasure to work, **Lorraine Headen** and **Madeleine Langford-Allen**. The production of *CavMag* and the various development brochures and materials have benefitted from the superb design expertise of **Matt Bilton**, the editorial skills of **Jacqueline Garget** and the production direction of **Jeremy Wilson** and **Martin Doig**. The development programme is an evolving entity and we are all looking forward to continuing the excellent *modus operandi* we have established with our colleagues in CUDO.

Malcolm Longair

Contents

If you would like to discuss how you might contribute to the Cavendish's Development Programme, please contact either Professor Malcolm Longair (**msl1000@cam.ac.uk**) or Professor Andy Parker (**HoD@phy.cam.ac.uk**), who will be very pleased to talk to you confidentially. Further information about how donations may be made to the Cavendish's Development Programme can be found at:

phy.cam.ac.uk/development

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