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News from the Cavendish Laboratory

The New Cavendish Laboratory

EDITORIAL

Exactly a year ago, we were delighted to report in CavMag 15 the intention of the then Chancellor of the Exchequer, George Osborne, to invest £75M to leverage further funding to enable the Cavendish Laboratory to be rebuilt. The last year has been one of frantic activity to complete the RIBA Stage 2 design by the end of 2016 and to fulfil all the requirements of Government in order to proceed with the project. Both activities are well on course and it is timely to report the outcome of the design process. By a piece of splendid timing, three of our Alumni were awarded the 2016 Nobel Prize in Physics. A very good way to start the year.

MALCOLM LONGAIR

INSIDE

Cover image, front and back:
This section shows how the basement is sited both to gain best vibration performance and to allow for possible height extension in the future. Above and beyond the Reception in the spacious 'public' zone the lecture theatres 'float', and above the smaller of them is the Tea Room, with a south-facing covered terrace at third-floor level.

NEWS

The third incarnation of the Cavendish Laboratory is now well into the design phase, and, although many details will surely change before we can walk around the completed building, enough has been decided that we can provide an impression of how some of the technical challenges are likely to be met.

The needs embodied in the design brief are a great deal more involved than when the Physics Department last went through this exercise in the 1960s. How can a diverse organisation like the Cavendish manage the task of balancing the different design constraints? It turns out that our own conclusions match those of Norman Foster, who commented, in reflecting on how his architectural practice dealt with complex projects:

"one of the earliest tasks on a project is to design operating structures and evolve methods of communication which will unite the separate interests in commonly shared objectives. Only then can the creative process be unleashed."

(in *Foster Associates, Buildings and Projects*, ed Ian Lambot,Vol 3, Watermark, 1989 ISBN 962 7274038).

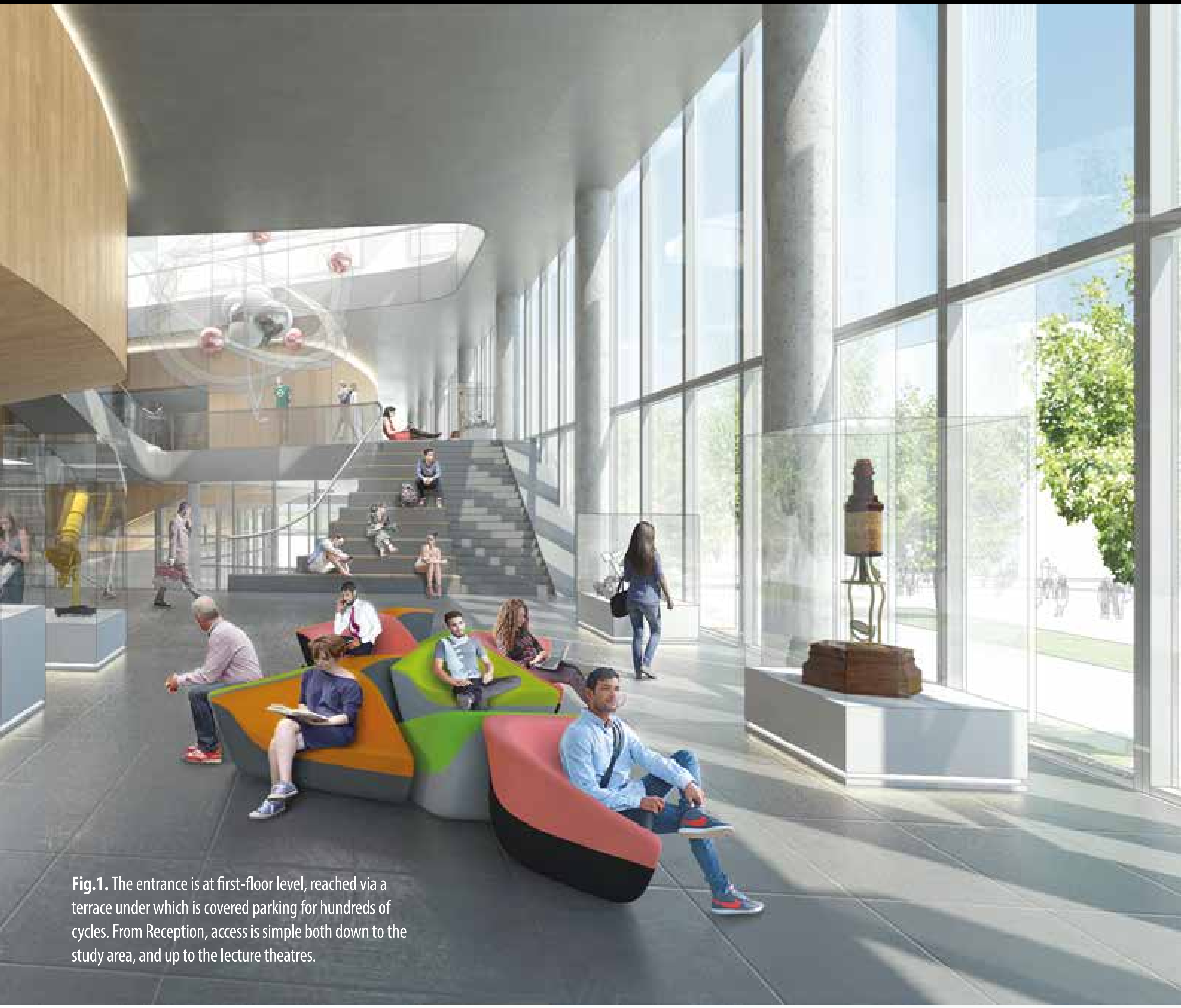


Fig.1. The entrance is at first-floor level, reached via a terrace under which is covered parking for hundreds of cycles. From Reception, access is simple both down to the study area, and up to the lecture theatres.

Within the Cavendish, the 'Logistics Committee', composed mostly of the scientists who will occupy the building, has steered internal discussions of the design and will ultimately manage the move into the new building. Taking the project to its present point has involved a great deal of discussion with the present members of the department, and every person among the 1000 or more regular users of the Cavendish has had the opportunity to make their own input into design specifications through various consultation fora. The Logistics Committee has provided a mechanism for resolving debates where different wishes conflict, and the emerging building design therefore represents a consensus view of an appropriate response to the diverse pressures to which the design is subject. The work in the Department has just been the tip of the iceberg. We have been fortunate indeed in working very cooperatively with the team of the lead architects, Jestico + Whiles, and in concert with diverse technical consultants providing expertise in every relevant aspect of building design, from accessibility to zoning of fire protection.

The photograph of the architectural model (Fig. 2) gives an impression of the dense occupation of the Veterinary School Paddock site which is needed to match the current area of accommodation. Though the scale of the laboratory will be very similar to the present provision in the first phase of the project, two extensions are being kept in mind to enable future expansion in a coherent manner. Intelligent

Fig. 2. A model of the building layout shows how the new building fills the Paddock site. Madingley Road is at the right, and J.J. Thomson Avenue at the bottom. The main entrance lies on J.J Thomson Avenue, and gives direct access to an open area housing two lecture theatres as well as an exhibition area. To the south (left) there will be a pleasant open area separating the Cavendish from another new building which will house many communal facilities including a full-scale canteen.

approach to environmental impact is a key feature of the design process, and so it is natural to provide at the front of the building extensive covered cycle storage, and related spaces for changing and showering – aids to long-term reduction in the environmental cost of travel to work in the Cavendish.

The entrance zone includes a Reception area embedded in a circulation space from which free access will be possible to various facilities used daily by staff, students and visitors. These include an adaptable study area, and lecture theatres of similar capacity to those in the present Cavendish to ensure the future delivery of our teaching in Part II and Part III. Innovation in teaching methods is reflected in a room with 'cluster seating', which is likely to make Examples Classes much more effective than has been possible in the older-style lecture theatres. The entrance zone also provides space for outreach activities which bring school-age children and members of the public to the department, responding to the lab's long-term commitment to this important activity. We anticipate that there will be some interesting displays in this public area of items of interest both from the historical collection of artefacts, and some exhibits of contemporary interest. These can be admired by visitors as they call in to the central administration area or the traditional Tea Room, both located on the top floor.

Unrestricted access to specialised laboratory spaces is no longer desirable for a number of reasons, and so the public zone is segregated from the research areas of the laboratory without the separation being too intrusive – and everyone based in the Department, and our undergraduates will be able to use their standard 'University Card' to allow them into the research wings and undergraduate labs. The latter will be comparable to the present open-plan Part I, and small Part II lab areas, and

Fig.3. The research and teaching wings are connected together by parallel north-south corridors on all levels. As well as giving very good connectivity across the site these corridors also enclose the internal courtyards, which will provide a pleasant outlook for the offices surrounding them. The research wings also have smaller courtyards set into the upper floor, which should create an excellent environment in the areas with high densities of offices.

should provide an excellent environment for carrying forward the essential tradition of exposure to 'hands-on' practical experience central to experimental physics education. The same wing of the building will house new facilities for the mechanical and electronic workshops, so there will be continuing provision of the capability of making things one cannot buy off-the-shelf.

The remaining space on the site houses the core of the research facilities, and the design directly reflects the strategy adopted for provision of the technical services for these laboratories and offices. This removes the main service functions to 'Central Utilities Buildings' at the end of each wing – physically separated by a small gap with a flexible seal, to isolate vibration. To promote the internal communication within the lab, dead-end corridors have been avoided, and there is extensive provision throughout of small areas and rooms for discussion, interaction and teaching. Research seminar rooms are distributed around the building in order to foster local interactions within and among research teams. Each point can be accessed by lifts and corridors without ramps or steps across the entire building, enabling the safe and easy movement of equipment around the department.

Specialised facilities have been aggregated to make efficiency gains where possible and to encourage sharing of equipment. There are therefore large areas given over to an integrated cleanroom, to a hall for large cryostats and magnets, and to deposition facilities for solid-state devices. To assist with future work in particle physics and astronomy a special facility is planned to enable assembly of large instruments destined for life underground at a particle accelerator, on a mountain-top observatory, or in orbit. To meet the needs of increasingly sensitive measurement methods there is an extensive basement within which

Fig.4. The view of the entrance to the new Cavendish Laboratory from the south.

the vibration performance will be at least as good as the best parts of the current site, and within which it will be much easier and more economical to attain tight temperature and humidity control than in our present leaky buildings. All of these diverse forms of provision should enable the Department to meet one of the objectives of the new building, in providing facilities which can be a national resource, rather than just answering local needs.

Naturally enough, many aspects of the design address the Department's current needs, and the concerns of contemporary physics. However, the unknown nature of physical science in 30, 40 or 50 years' time has been a factor in the specification of the building. The design team is not clairvoyant, and so the proposed structure embodies completely open opportunities in the second phase of building, and a high degree of future flexibility in the potential for rearranging internal spaces. In some areas office and laboratory provision can be swapped around as needed. Through much of the building it will be possible to remove and relocate walls dividing up the space. Adaptability comes at a price, but where possible a high degree of flexibility is inherent in the design. The entire team working on the New Cavendish Laboratory is aiming to make a fitting successor to its two predecessors, and provide future generations of physicists in Cambridge with outstanding conditions for 'unleashing the creative process' in ways we currently cannot even imagine.

RICHARD PHILLIPS, on behalf of the Logistic Committee and the project team.

The 2016 Nobel Prize in Physics awarded to three Cavendish Alumni

We warmly congratulate DAVID THOULESS, DUNCAN HALDANE and MICHAEL KOSTERLITZ on the award of the 2016 Nobel Prize in Physics for their discoveries in theoretical condensed matter physics. The citation states that the award was:

'for theoretical discoveries of topological phase transitions and topological phases of matter.'

Half the award went to David Thouless and the other half was equally shared by Michael Kosterlitz and Duncan Haldane. All three were undergraduates in the Cavendish Laboratory where they took the Theoretical Physics option. Nigel Cooper has kindly written a gentle introduction to the significance of topology for condensed matter physics which accompanies this biographical note.

David Thouless is Professor Emeritus of Physics at the University of Washington. He was born in Bearsden in 1934 and educated at Winchester College. He was an undergraduate at Trinity Hall where he read Natural Sciences. He obtained his PhD at Cornell University under the supervision of Hans Bethe. He was an Assistant Lecturer (1961-63) and then Lecturer (1963-64) in the Department of Applied Mathematics and Theoretical Physics at Cambridge. He was appointed a Fellow of Churchill College, becoming the College's first Director of Studies for Physics in 1961. He then took up the Professorship of Mathematical Physics at the University of Birmingham in October 1965 where he remained until 1978. During this period, he began his collaboration with Michael Kosterlitz. He was elected a Fellow of the Royal Society in 1979. In 1983 he was appointed Royal Society Research Professor in the Theory of Condensed Matter (TCM) group in the Cavendish Laboratory and became a Professorial Fellow of Clare Hall. He returned to the USA where he took up the post of Professor of Physics at the University of Washington in September 1986.

Michael Kosterlitz is the Harrison E. Farnsworth Professor of Physics at Brown University. He was born in Aberdeen in 1942 and came up to Gonville and Caius College where he graduated with a BA in Physics in 1965. He obtained his DPhil in high energy physics from Oxford University in 1969. He became a Research Fellow at the University of Birmingham in 1970 but soon changed fields to collaborate with David Thouless on phase transitions driven by topological defects. In the early 1970s, they overturned the then current theory that superconductivity or superfluidity could not occur in thin layers. They demonstrated that these could occur at low temperatures. They also explained the phase transition mechanism that makes superconductivity disappear at higher temperatures. He became a lecturer at Birmingham in 1974, working on critical phenomena in two and higher dimensions. He took up his faculty post at Brown University in 1982.

Duncan Haldane is the current Eugene Higgins Professor of Physics at Princeton University. He was born in London in 1951 and educated at St Paul's School. He came up to Christ's as an undergraduate in 1970 to read Natural Sciences in which he graduated with a BA in the Theoretical Physics option. He carried on to study for a PhD in the Theory of Condensed Matter Group under the supervision of an earlier Nobel Prize-winner Phil Anderson. His PhD was conferred in 1978. He was elected a Fellow of the Royal Society in 1996.

In the 1980s, David was able to explain a previous experiment involving very thin electrically conducting layers in which conductance was precisely measured as integer steps. He showed that these integers were topological in nature (see the article by Nigel Cooper). At about the same time, Duncan discovered how topological concepts can be used to understand the properties of chains of small magnets found in some materials.

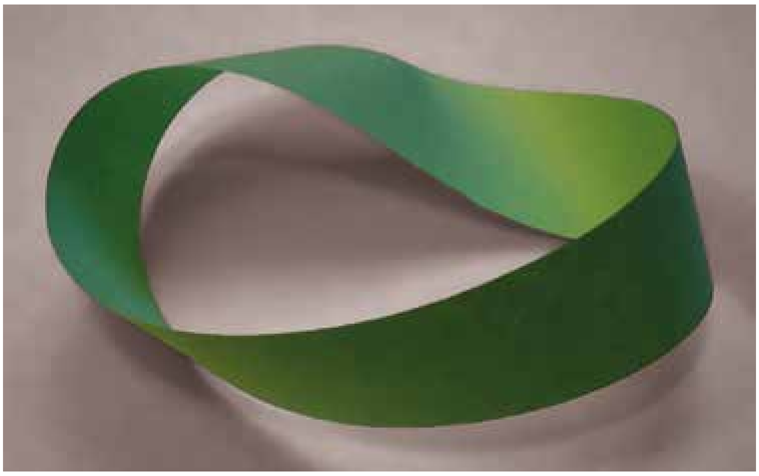
Over the last decade, the practical application of topology has boosted frontline research in condensed matter physics, not least because of the hope that topological materials could be used in new generations of electronic devices and superconductors, or in future quantum computers.

BEN SIMONS AND MALCOLM LONGAIR

Topology Matters
the 2016 Nobel Prize in Physics

NIGEL COOPER explains the remarkable physics behind the award of the 2016 Nobel Prize in Physics to three Cavendish Alumni.

Topology is a mathematical concept that refers to certain properties that are preserved under continuous deformations. One familiar example is the number of twists put into a belt before its buckle is fastened. Usually we aim to fasten a belt without any twists. But if we were to introduce a single twist we would produce a Möbius strip (Figure 1). No continuous deformation of the closed belt would get rid of this uncomfortable twist. The number of twists is said to be a 'topological invariant' of the closed belt.



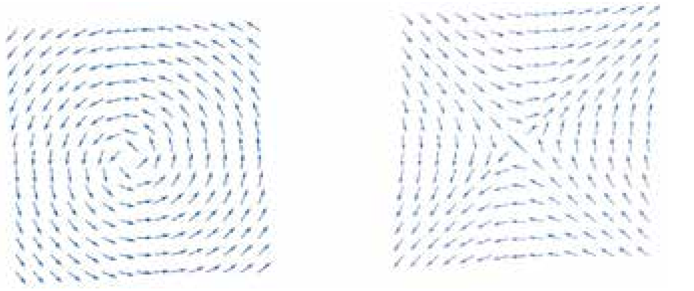
David Thouless, Duncan Haldane and Michael Kosterlitz (see previous article) showed how topological invariants can play important roles in determining the properties of matter. They were awarded the 2016 Nobel Prize in Physics *'for theoretical discoveries of topological phase transitions and topological phases of matter.'*

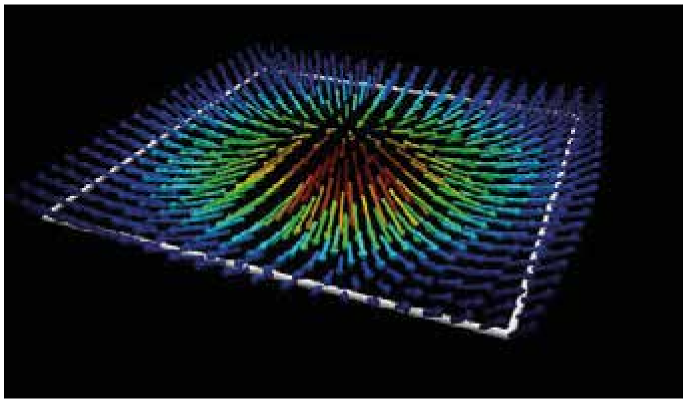
One such discovery concerns the thermal properties of certain types of two-dimensional (2D) materials, in which the state of the system is encoded by an angle θ that varies with position *(x,y)*. This angle could represent, for example, the local direction of the magnetic moment in a thin ferromagnet layer, or the local phase in a thin film of superfluid or superconductor. A twist of θ through 360° around some closed loop creates a 'vortex' or an 'anti-vortex' depending on the sign of the twist, which cannot be removed by continuous deformations (Figure 2). Kosterlitz and Thouless showed that the thermodynamics of such systems are controlled by the behaviour of these topological objects. They predicted a new phase of matter in which each vortex is faithfully paired with its own anti-vortex, and a thermally-driven phase transition to a chaotic high-temperature regime where vortices and anti-vortices uncouple and roam freely. These predictions were confirmed by experiments on superfluid helium films and on ultracold atomic gases.

A very different way in which topology enters materials science involves the quantum states of electrons moving in crystals. The pioneers of quantum mechanics understood that the electronic states in crystals are described by energy bands as a function of electron momentum. One of the triumphs of the early quantum theory was to show how the occupation of these bands by electrons could explain the difference between insulators, in which all bands are either filled or empty, and conductors in which one or more bands is partially filled.

Remarkably, Thouless and his co-workers showed that this long-standing theory overlooks crucial topological features in 2D crystals. An example of a naturally occurring 2D crystal is graphene, and artificial 2D crystals can be made in semiconductor quantum wells. Specifically, each energy band can be assigned a topological invariant, C, related to how the quantum wavefunction of the electron 'twists' in momentum space, (p_x, p_y) (Figure 3). This integer C is invariant under continuous changes of material properties, 'continuous' meaning that the energy gaps to other bands should not close. This is not just a mathematical curiosity - the value of C has direct physical consequences. Namely, if the band is filled with electrons, then rather than behaving as a conventional insulator, the material will show an unusual form of electrical conductivity known as the 'integer quantum Hall effect'. This effect was discovered in experiments by Klaus von Klitzing, Gerhard Dorda and Michael Pepper who was then at the Cavendish. A voltage drop V_x along the *x*-direction induces no current I_x in that direction, as in a conventional insulator, but it does induce a transverse 'Hall' current I_y. The ratio I_y/I_x was found to be quantized at integer multiples of the fundamental unit of conductance e^2/h as the magnetic flux density *B* changes (Figure 4). Thouless and his co-workers showed that this integer is the topological invariant *C* of the energy band. Their result is intimately related to the fact that, although the filled band requires there to be an energy cost to excite an electron to a higher energy state in the *bulk* of the sample, if C is non-zero there must be gapless, metallic, states on the surface to carry the Hall current. This current flows without energy loss, indicating that the surface behaves as a perfect metal.

This work, combined with insights from Haldane, has underpinned a recent revolution in our understanding of band insulators. Once the coupling of the electron spin to its translational motion is included, there appear topological invariants not only in 2D but also for 3D materials. These 'topological insulators' have the property that, while their bulk is insulating, their surfaces are conducting – and in a special way that leads to near-perfect metallic properties even when disordered. Experiments have confirmed the existence of topological insulators in many compounds. These topological phases of matter have opened the door to new forms of electronic materials and new devices which have the potential to transform future technologies.





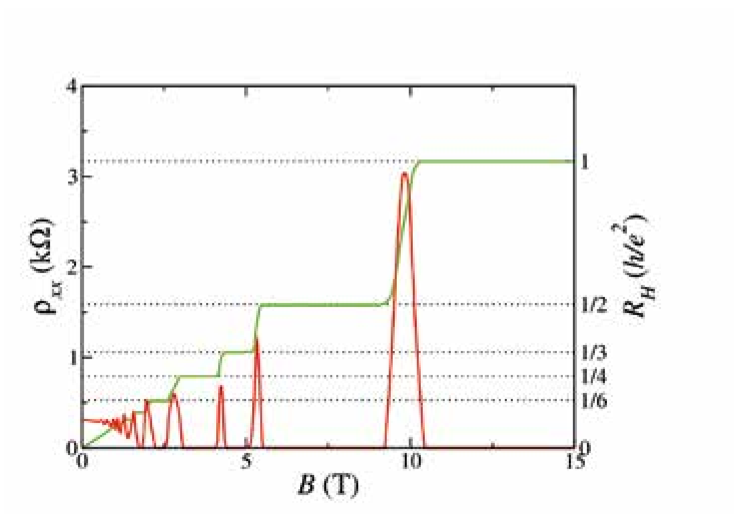


Fig.1 (left). A Möbius Strip [from Wikipedia/David Benbennick].

Fig. 2 (top). A vortex and an anti-vortex in a 2D material. The angle *θ(x,y)* of the local order, the spin of a ferromagnet or the phase of a superfluid/superconductor, changes by either plus or minus 360º around a closed loop.

Fig. 3 (middle). Topological configuration for an energy band in a 2D crystal. The two dimensions denote the electron momentum (p_x, p_y) and the local three-component unit vector represents the quantum state at that momentum. (Colours indicate the z-component of this unit vector.)

Fig. 4 (bottom). Typical magnetic field dependence of $\rho_{xx} = V_x/I_x$ (red) and $R_H = V_y/I_x$, the Hall resistance (green), in the quantum Hall effect.

Interactions between electrons, and between experimenters and theorists

CHRIS FORD of the Semiconductor Physics Group describes the ongoing quest for producing and controlling quantum matter which promises many technological advantages, including higher temperature superconductors and quantum computers. The path to success lies through understanding the nature of quantum particles in solids and more importantly the interactions between them.

Electrons moving in a conductor, such as a metal or semiconductor, interact very strongly with each other through the Coulomb force. Nevertheless, the theory we all learn as undergraduates largely treats them as individual particles or waves, moving with occasional scattering. Theory tells us that they can often be treated as particular excitations of an interacting system. Some of these excitations can preserve their identity for a significant length of time and are called *quasiparticles*. Imagine an infinite array of springs joined together as shown in Figure 1. If you pull one junction to the side and let go, all the other springs will eventually start moving, fairly randomly. If, however, you send a plane wave through the array, it should just move along without spreading out and so will retain its identity. The quantum-mechanical equivalent is a wave with a particular momentum – a form of quasiparticle.

Finding a suitable quasiparticle theory for a given system is complicated and contains huge approximations, so it must be tested by experiment. That's where we come in – in the Semiconductor Physics Group we design and make conducting structures where we can confine electrons in sheets, wires or artificial atoms, see them behaving as waves or particles, and map out their wave functions or energy-momentum dispersion relations.

To do this, we use a gallium arsenide (GaAs) crystal as the starting point, as we can grow it with ultra-high purity and crystal quality, using the technique known as molecular-beam epitaxy (MBE). MBE deposits one atomic layer of crystal at a time and so it is easy to change the crystal composition within a monolayer, just by opening or closing a shutter, to switch to growing a layer of a material containing a proportion of aluminium (AlGaAs), which has a larger band-gap than GaAs, or to incorporate silicon atoms in particular layers to donate electrons. In this way, electrons collect in a potential well at the interface between GaAs and AlGaAs, and are kept separate from the charged silicon donors in the AlGaAs. They can therefore travel relatively long distances, tens of microns at low temperatures, without being scattered. We then pattern the surface of the material with metal 'gates', and apply negative voltages to each to deplete the electrons, controlling their confinement and density.

Squeezing electrons into a truly one-dimensional (1D) wire of extremely high quality amplifies their quantum nature to the point that it can already be seen by measuring the energies and wavelengths (or momenta) of the electrons that can be injected into the wire—think of a crowded train carriage, with people standing tightly packed all the way down the centre of the carriage. If someone tries to get in a door, they have to push the people closest to them along a little to make room. In turn, those people push slightly on their neighbours, and so on. A compression wave passes down the carriage at a speed related to how people interact with their neighbours. By measuring this speed, one can learn about the interactions.

The same is true of electrons in a quantum wire – they repel each other and cannot get past and so, if one electron enters or leaves by 'tunnelling' in from a region nearby, it excites a compressive wave as would the people in the train. However, electrons have another characteristic, their angular momentum or 'spin', which also interacts with their neighbours. Spins can also form a wave carrying energy along the wire, and this spin wave travels at a different speed from the charge wave.

Measuring the wavelength (or momentum) of these waves as the energy is varied is called tunnelling spectroscopy. We use patterned gates on the surface of a wafer of GaAs to define an array of 1D wires in a quantum well just above another two-dimensional layer, which acts as a spectrometer. Momentum and energy must be conserved in tunnelling between the layers, though a magnetic field B directed in the plane of the wires and the applied inter-layer voltage V_{dc} add extra momentum and energy, respectively.

We measure the current I flowing between the layers. Figure 2 shows a map of d^2I/dV^2_{dc} as a function of momentum and energy. Each occupied 1D state below the Fermi energy contributes a parabola, corresponding to the dispersion relations of the corresponding 1D subband. When the gate voltage is not very high, two such parabolae are clearly visible. Even though there are actually 6000 wires in parallel in order to enhance the very weak tunnelling current, the lithography is so good that they are all highly uniform and hence we can see that the same number of subbands is occupied across the whole array. Using such arrays, but with a large gate voltage to deplete the wires down to the last 1D subband, we detected the separate spin and charge waves predicted for an interacting 1D system (Jompol *et al.*, *Science* **325**, 597, 2009), a major milestone in the confirmation of this 'Tomonaga-Luttinger-liquid' theory.

We noticed at the time that the spin-charge separation could be seen at much higher energies than those for which the

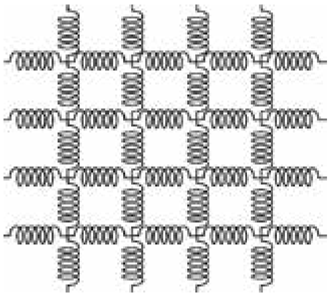


Fig. 1. A set of coupled springs resembles the electrons in a conductor interacting with each other.

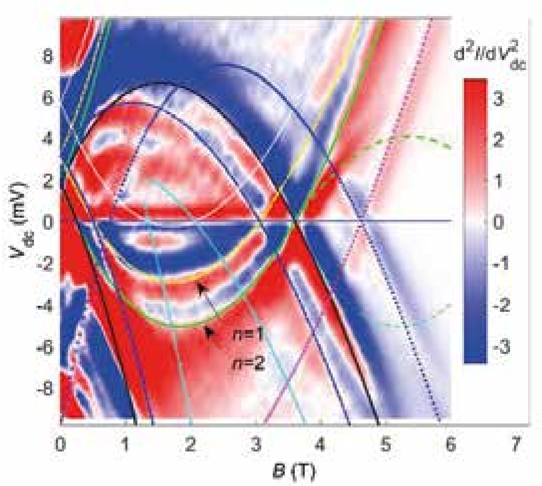


Fig. 2. d^2I/dV^2_{dc} as a function of the energy (proportional to the bias V_{dc} applied between the 1D and 2D layers) and momentum (proportional to in-plane magnetic field B). Two parabolae, each corresponding to a 1D subband, are labelled *(n = 1, 2)*.

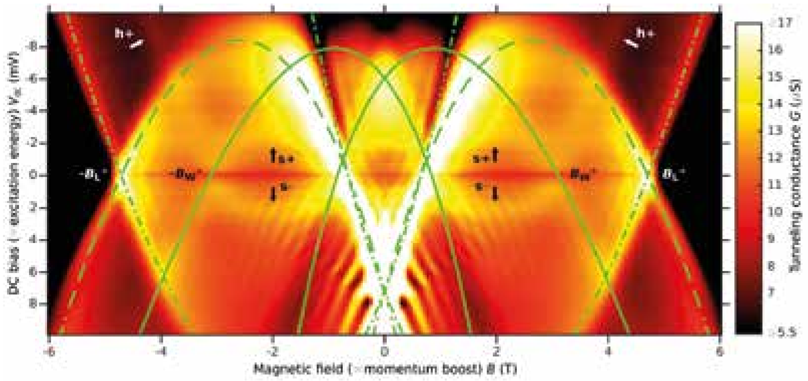


Fig. 3. *dI/dV$_{dc}$* as a function of momentum and energy for an array of very short wires, just 1 µm long, measured at very low temperatures (50 mK). The unique replica feature is labelled s+.

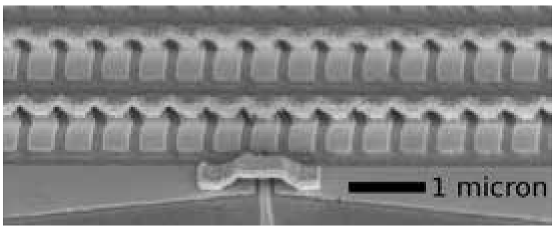


Fig. 4(a). Scanning electron micrograph of air bridges connecting together an array of gates.

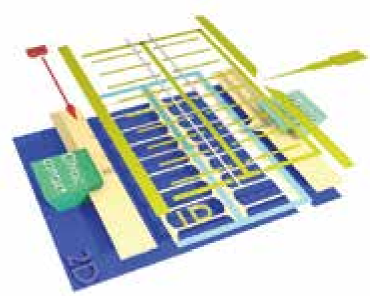


Fig. 4(b). Schematic 3D image of the device, starting with a 2D layer of electrons at the bottom, then an array of 1D wires, a set of surface gates to define the wires and to inject current through a constriction into just the wires rather than the 2D electron gas, and finally air bridges to make electrical contact to the isolated gates. Ohmic contacts bring electrons in from metallic leads to the two layers of electrons.

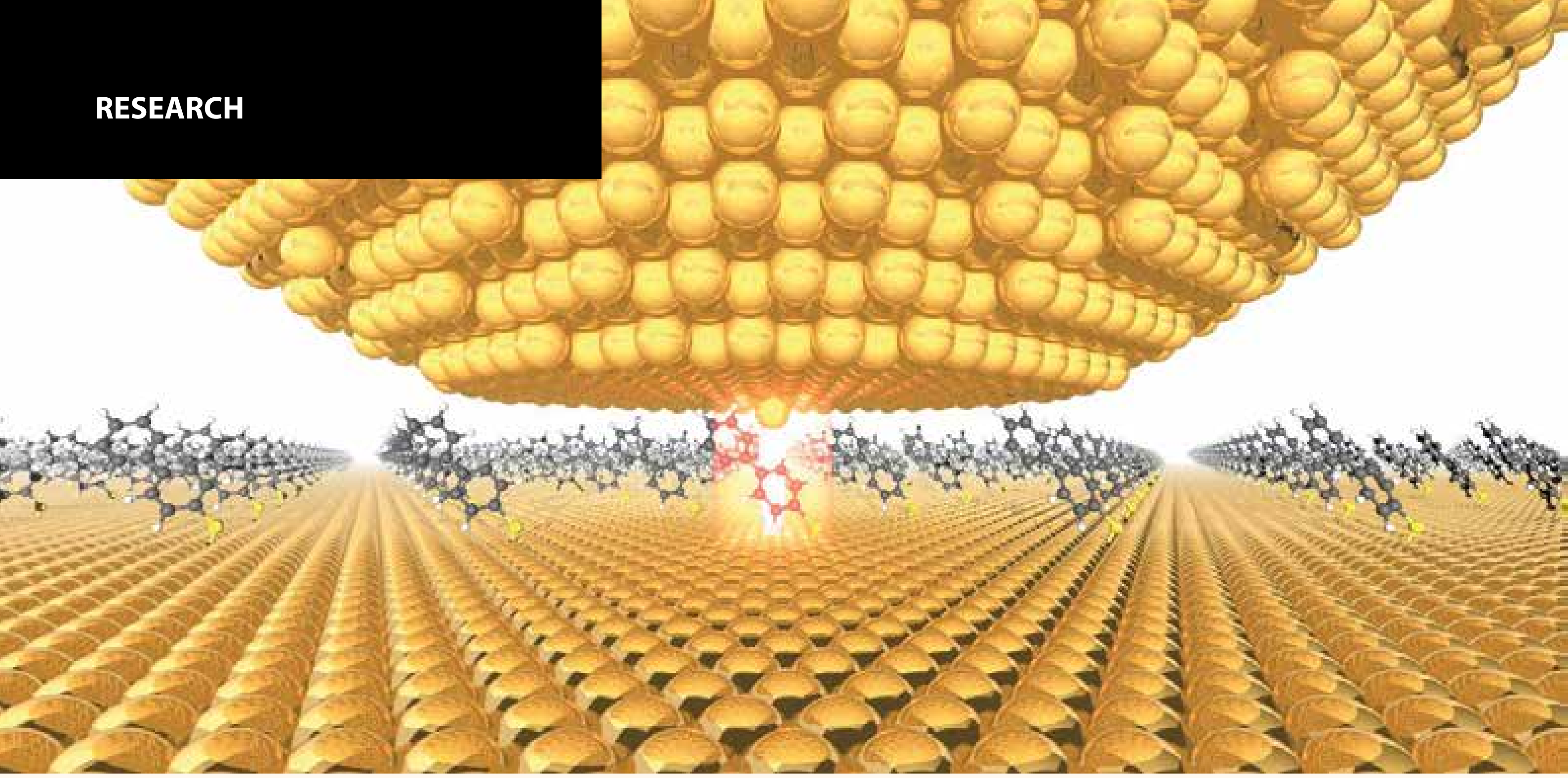
Luttinger-liquid theory is valid – that theory is based on the approximation that energy is linearly proportional to momentum around the Fermi energy. Coincidentally, a new theory, published the same year, led to new intriguing predictions of extra ways of exciting waves among the electrons – it is as if the person entering the train pushes so hard some people fall over and knock into others much further down the carriage. These new 'modes' are weaker than the spin and charge waves and so are harder to detect.

We started on the long road to testing the new theories, which predicted 'replicas' of the usual curves, at higher momentum which we can probe by changing the magnetic field. I asked our theoretical collaborators in Birmingham how large the signal from these replicas should be - theorists are notoriously vague about such minor details! Six months later the answer came back – there should be a hierarchy of modes corresponding to the variety of ways in which the interactions can affect the quantum-mechanical particles, and the weaker modes should be strongest in very short wires. So we developed new device designs with shorter wires, from 10 down to 1 micron in length. By varying the magnetic field and voltage, the tunnelling from the wires to an adjacent sheet of electrons could be mapped out, and this revealed evidence for the extra curves predicted by the theory. This is labelled s^+ in the plot of the tunnelling signal in Figure 3, in which it can also be seen as an upside-down replica of the usual spin curve labelled s^-.

To make an array of such short wires, we had to devise a way of making contact to a set of 6000 narrow strips of metal that are used to create the quantum wires in the semiconductor material below. This required an extra layer of metal in the shape of air bridges between the strips, as shown in the picture taken using an electron microscope and the schematic diagram of the structure (Figures 4(a) and (b)).

No other team has the capability of making similar devices, and we are now constructing a new generation of devices to show how the strength of the replica varies with wire length more clearly. This work will inspire theorists to press on studying interacting systems further, confident that their approximations are not too simplistic to capture the essence of this complex behaviour.

I gratefully acknowledge the major contributions of **YODCHAY JOMPOL, YIQING JIN, MARIA MORENO** and other members of the team to the success of this project.



Optics goes Atomic

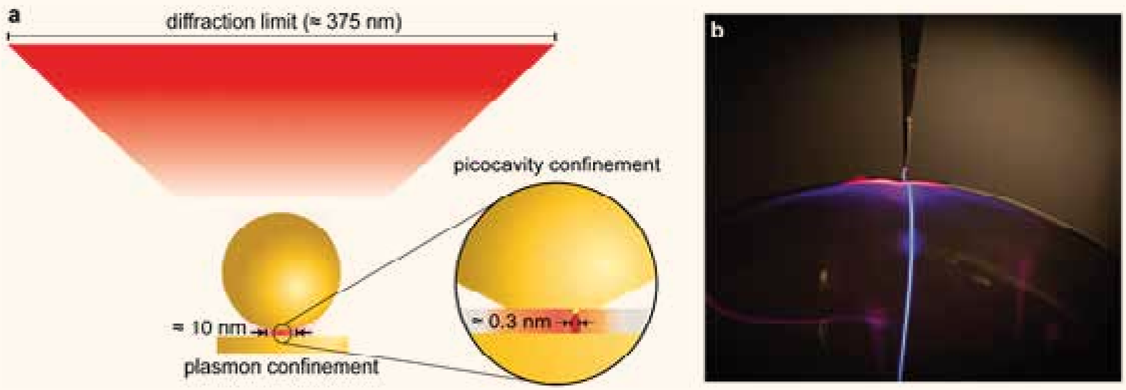
JEREMY BAUMBERG describes how to achieve optical imaging down to atomic scales.

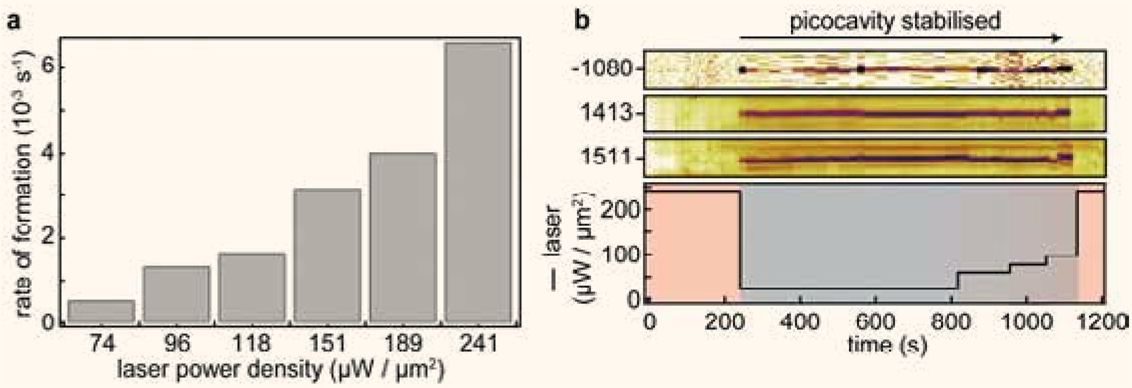
For more than a century it was believed that the resolution of every optical system is limited by diffraction. However our recent work shows we can in fact trap light to the atomic scale. The diffraction limit, first formulated by Ernst Abbe in 1873, states that light with wavelength λ can only be focused to a spot with diameter given by ~ λ/2.

Nowadays several methods already exist to circumvent partly this limitation, including super-resolution microscopy for which the 2014 Nobel Prize in Physics was awarded. Such methods are based on the idea that as long as emitters are spaced far enough apart we can determine their position with sub-diffraction-limited precision. We have, however, developed a completely different approach, which turns out to allow us to watch single molecules flex and bend in real time, and is based on localised 'plasmons'. These are surface-bound quasiparticles made of coherent collective electron oscillations tethered to photons. Due to their electron component, plasmons do not suffer from diffraction and can be used to confine electromagnetic fields to the scale of several nanometres. However, this resolution is still fuzzy compared to the size of single molecules.

Our recent breakthrough shows how we can now confine light to the volume of a single atom (1), using cascading coupling: we first focus laser light to a diffraction-limited spot which excites localised plasmons in a tiny nanostructure. These plasmons are then focussed even further inside a few-atom-thick gap by atomic protrusions that form 'picocavities' having sizes around 0.3nm (Fig.1a). This localisation of light to atomic protrusions is the optical equivalent of the 'lightning rod effect' - the fact that fields are always strongest around sharp features. We can visualise this effect by bringing a metallic tip close to a conventional plasma sphere - right at the tip the field becomes strong enough to develop local sparks (Fig.1b). Together with our collaborators, we were able to show that single gold atoms can similarly localise a plasmonic field.

To study this plasmon localisation we use an easy-to-make 'nanoparticle-on-mirror' geometry (2,3). In this construct, gold nanoparticles are placed on a continuous gold film but spaced above by a thin rigid molecular layer. The plasmons in the nanoparticle couple to induced image charges in the gold film below, creating an extremely tightly focused plasmonic field in the gap region, which concentrates the light a thousand-fold. To form picocavities we use the fact that





gold surface atoms are actually quite mobile at room temperature and its surface shows constant reconstruction. This process is very hard to control at room temperature because thermal energies are already sufficient to allow surface diffusion. However, at cryogenic temperatures (here 10 Kelvin) the surface atoms are frozen into place and can only move when triggered by laser illumination. Illuminating our sample with a red laser and recording the vibrational spectra of our molecular layer, we were able to identify the point at which single atoms are pulled out of the surface and a picocavity is formed. Both formation and destruction of these picocavities can be controlled through the laser power - higher intensities lead to a higher rate of formation (Fig. 2a). Once a picocavity is formed we freeze it in place by dropping the laser power, allowing observation over many minutes (Fig. 2b).

Picocavities dramatically enhance the coupling of individual molecular vibrations to the plasmonic field due to their tight localization and massive intensity. It turns out that this interaction is identical to opto-mechanical effects that limit gravitational wave detectors (12 orders of magnitude larger!), and our 'molecular optomechanics' opens up all sorts of new possibilities for treating molecular bonds as springs which we can pluck. It opens up potentially new routes to optically catalyse chemical reactions by amplifying or damping particular sets of vibrations. First preliminary experiments (unpublished) show that pumping vibrations using much higher intensity pulsed lasers indeed leads to chemical transformation of the molecules. Our next big challenge will be obtaining control over this process to select one particular reaction pathway. Finally though, we are really 'seeing' atoms and molecules on the smallest scale in real time and ambient conditions, and realising undreamt of possibilities to move and control them through nanophotonics.

Fig. 1: a (top left) Illustration of cascading coupling of light to localised plasmons to picocavities. Light focussed by a lens (from top) is first coupled into the gap underneath the nanoparticle, and then trapped at a single atom protrusion. **b (top right)** The lightning rod effect visualised by bringing a sharp metallic tip close to a plasma ball.

Fig. 2: a (bottom left) Rate of picocavity formation for different laser power densities. **b (bottom right)** Stabilisation of a picocavity by reducing the laser power after the formation was detected. The picocavity stays stable for more than 10 min and is only destroyed when the laser power is increased again.

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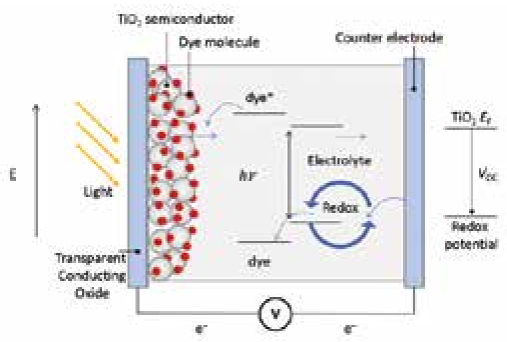
Data-driven molecular engineering of solar-powered windows

JACQUI COLE is head of Molecular Engineering at the University of Cambridge - a joint initiative between the Cavendish Laboratory and the Department of Chemical Engineering and Biotechnology, in partnership with the STFC Rutherford Appleton Laboratory, UK. She is also the current recipient of the 1851 Royal Commission 2014 Fellowship in Design. Jacqui describes the new project she and her team will be carrying over the next few years.

More people are now living in urban environments than in rural communities. This major shift in urban demographics is adding to the burden of global energy resources. Since buildings are the centrepiece of modern living, building use has become the main drain on our energy resources. As an example, it comprises 40% of the total energy consumption in the USA. The embedding of new environmental technologies into future cities to realize energy-sustainable buildings is therefore paramount to offsetting the global energy crisis.

Dye-sensitized solar cells (DSCs) present a possible solution. They involve next-generation environmental technologies that have prospective applications as solar-powered windows – windows in buildings that generate electricity from sunlight. DSCs are particularly attractive in 'smart window' applications since they offer a transparent and lowcost photovoltaic device that can be impregnated into glass. The closest technological 'smart window' contender to DSCs is building-integrated silicon photovoltaics. Very thin films of silicon are required however to achieve the necessary transparency for a 'smart window'. Once they are sufficiently thin, their photovoltaic efficiency is less than that of DSCs which boast a current world-record efficiency of 14.3%. DSCs are also very cheap to manufacture relative to other types of solar cells, and they operate well under ambient light conditions, ideal for citydwelling environments.

Despite the vast prospects for DSC-based solar-powered windows, innovation is being held up by a materials bottleneck. More suitable dye molecules are required to overcome the market economics that are driven by price-to-performance ratio. The materials discovery of a new dye that is slightly cheaper or just a fraction higher in device efficiency could be all that is needed for innovation to succeed.



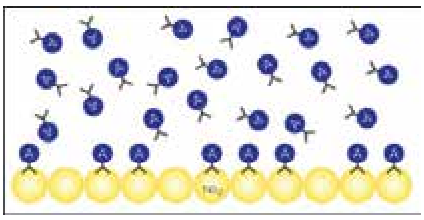


Fig. 1. The operational mechanism of a dye-sensitized solar cell.

Fig. 2. A schematic representation of dye molecules approaching and binding onto a TiO_2 surface to form the working electrode of a dye-sensitized solar cell.

In our group, we seek to overcome this materials bottleneck through a new project in collaboration with the Argonne Leadership Computing Facility (ALCF) at the Argonne National Laboratory in the USA. This collaboration arose from my receipt of the award of one of the two Tier 1 data science projects that the ALCF issued as part of a worldwide competition. The ALCF hosts one of the world's largest supercomputers, which the team will now exploit using a large-scale data mining approach coupled to machine learning to discover new classes of DSC dyes.

Dyes that harvest a more panchromatic region of light from the Sun are key targets, as are materials that inject electrons more efficiently into the TiO_2 conduction band - the process that initiates the electrical current in DSC devices, as indicated in Figure 1 which illustrates how a DSC works.

The manner by which dye molecules approach and bind onto the TiO_2 surface to form the dye-TiO_2 interfacial structure that comprises the DSC working electrode, will also be studied (Figure 2). Such large-scale simulations will be performed in tandem with complementary experiments, where their symbiotic nature will form a judicious materials-by-design workflow.

Beyond the direct objectives of this materials discovery program, this research also points the way to the ultimate goal of molecular engineering, which is to be able to tailor-make molecular structures to suit a given device application.

The Versatility of Computational Condensed Matter Physics

We welcome back EMILIO ARTACHO who joined the Laboratory in 2011 as Professor of Theoretical Mineral Physics from the Department of Earth Sciences. Over the last five years he has been deeply involved in leading major research projects in his native Spain. Specifically, he joined Nanogune, an international Nanoscience Research Institute in San Sebastian, where he led the Theory group. He is also a member of the Donostia International Physics Centre (DIPC) and of the Basque Foundation for Science Ikerbasque. Emilio describes his principal research interests.

My research is in theoretical condensed matter physics using computer simulations. Computational physics is probably the earliest instance of what we now call virtual reality, but instead of risking our lives by looking for Pokemons on the streets, we simulate nature as accurately as possible in what can be thought of as virtual experiments. These are validated by comparison with real experiments, which then provide a wealth of complementary data, offering new insights that improve our understanding. My main interests are in low-energy condensed matter physics at the atomic scale, mostly using first-principles simulation techniques.

These types of simulation can be very versatile: if a simulation box is filled with, say, a thousand atoms, there is not so much difference so far as the technology is concerned if they happen to represent a piece of DNA in water, a component of a photovoltaic cell, or a piece of material hypothesised to exist deep in the interior of Jupiter. My career reflects this flexibility, having followed my curiosity in many different directions while developing the simulation tools that would enable me to push back the frontiers in any of them. In particular, during the last twenty years, in collaboration with my colleagues, we developed a method called Siesta, which was pioneering at the time, for large-scale, linear-scaling, density-functional-theory calculations to address the demands of our science interests. Most recently, my research has been following three main strands: non-adiabatic effects in radiation damage, wet systems and functional oxides, all three directions reflecting the ten years I enjoyed as a member of the Cambridge Department of Earth Sciences up to 2011.

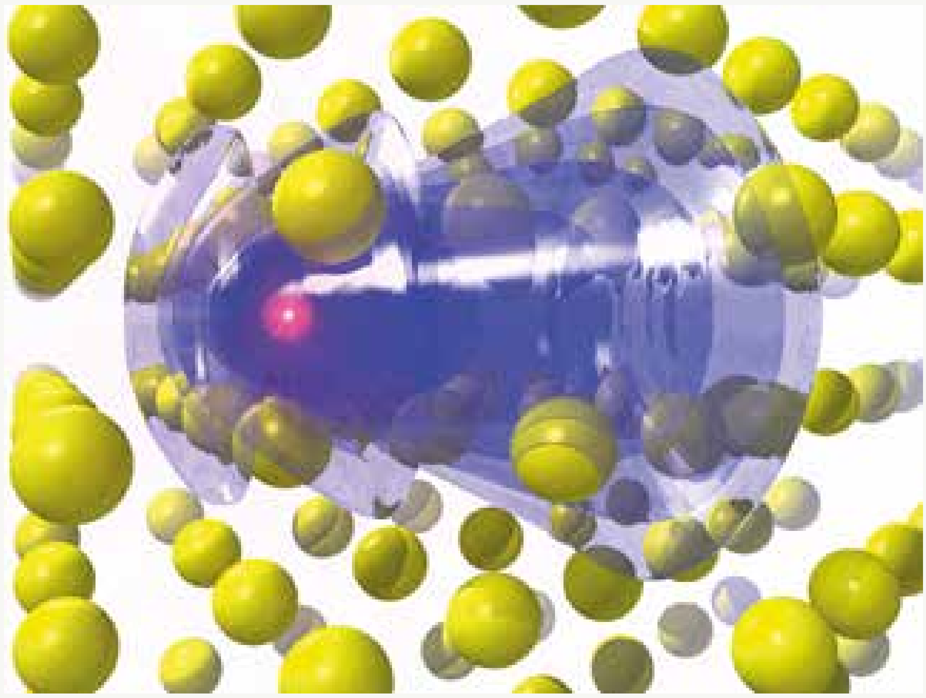


Fig. 1. Isosurfaces of electron density (blue) for an intermediate energy proton passing through bulk aluminium (image by Alfredo Correa)

An important effort at the Department of Earth Sciences was the exploration of possibilities for the safe disposal of nuclear waste, in particular, the question of to what extent and how electrons are implicated in **radiation damage** processes. This is well understood for very high and very low energies, but scarcely anything was known for intermediate energies for the systems of interest. A line of research was started a decade ago on the first-principles description of strongly non-adiabatic and out-of-equilibrium processes relevant to the question. Using time-dependent density-functional theory we calculated the rate of energy transfer from an ion projectile to different kinds of host materials, and the results of the calculations provide insights on the key processes involved (Figure 1).

Continued overleaf...

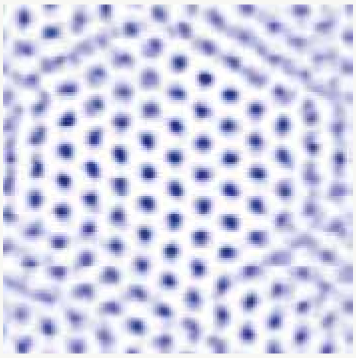


Fig. 2: An image of the predicted distribution of positions of oxygen atoms in the hexatic phase found for water confined to two molecular layers, showing the shear displacements produced by moving dislocations, as predicted by the theory of two-dimensional melting (image by Jon Zubeltzu).

By **wet systems** I mean liquid water and its interactions with other forms of matter. Liquid water itself is a very intriguing system with over seventy different anomalous forms appearing on various web-sites, starting with the best known of them, floating ice. Liquid water's peculiarities stem from the relative structural disposition and dynamics of water molecules in the liquid, which depend very subtly on the balance between directed hydrogen bonds and non-directed dispersion interactions among molecules. For a number of years, we have been trying to understand what can be learned about these problems from first-principles molecular dynamics simulations. We have found the system to be extremely subtle and challenging for density-functional theory, but important insights have been provided about the interplay between the above-mentioned interaction balance and the anomalous properties of the liquid. We are now exploring the response of water to nano-scale confinement. We were surprised to find that under some conditions very thin films of water become very simple, a word rarely used to describe these systems. The liquid is predicted to freeze as if it were made up of layers of Lennard-Jones spheres, including an intermediate hexatic phase (Figure 2). The key to this would be the almost-free rotation of the hydrogen atoms around those of oxygen while they transform to ordered forms.

Oxide materials display many interesting features that have been, and can be, exploited technologically, including their structural, elastic, magnetic, dielectric and superconducting properties. We have been working for some time on thin films of perovskite oxides, originally intrigued by the appearance of a two-dimensional electron gas at the interface between such a film and the substrate on which it sits. The origin of this gas was finally characterised as a topological feature, a high topical field at the moment (see pages 7–9). The insights gained have allowed us to propose interesting interactions of such a gas with ferroelectric films with the aim of creating functional materials with different control parameters. In this case, the switching of the polarisation of the film would connect or disconnect the gas.

There is always a fourth unstated strand in our research group, namely the role of serendipity and collaboration opportunities leading to new challenges. In fact, part of the research activities described above was how these projects started. In spite of my best efforts under the pressure of Research Councils and European Commissions, I have never been able to predict exactly what will come about through this fourth strand. I do know, however, that it is the one that has produced the best research outcomes.

Explo

JACOB BUTLER describes how the Cambridge Colleges' Physics Experience (CCPE) enabled school students to design and build their own Mars Rover

November saw the first of our new Year 7 and 8 CCPE sessions. As for our Y9, 10, 11 and 12 CCPE programmes, students spent the morning in a host college, assigned according to the universities area link scheme, and then the afternoon in the Cavendish Laboratory.

The physics half of the programme has been developed to introduce 11- and 12-year-old students to the methods and applications of physics. It does this through a series of talks, demonstrations, and practical experiments that build on the Key Stage 3 syllabus. The day is themed as a Mars Rover mission, with the students divided into teams to produce the most effective and efficient solution to a series of problems based around space exploration.

Each team is further divided into groups that focus on different aspects of the mission, such as the design of the rover and lander. Though the groups work separately, an emphasis is placed on the collaborative nature of science and many of their findings are useful to the rest of the team. The groups each have a series of questions to answer that introduce them to the topic they will be working on, a demonstration that explains the key ideas, and an experiment for which they must develop and test their own solutions.

The main experiments test the students' rover and lander designs in situations that reflect the systems

Images, clockwise from top:

Testing the rover on sand and boulders

Students adding the final touches to the Mars Rover's wheels

Jacob demonstrating how the properties of a material change at different temperatures

ring Mars

used by space agencies such as NASA and ESA. The students' rovers are tested on a sandy, rocky surface similar to models of Mars, and a layered diorama designed to show the effectiveness of any suspension system.

The students choose the materials used to build their landers and their designs are tested using an accelerometer; the groups aim to produce the lowest measured acceleration. Two other groups look at data transmission and rocketry, investigating how faint signals can be amplified and the forces that underpin the operation of rockets.

Responses to the day were good, with both the teachers and students giving positive comments. These events take place as part of wider programmes for different age-groups that runs throughout the year. More details can be found at **https://outreach.phy.cam.ac.uk/programme/CCPE**

The Hydrogen Epoch of Re-ionisation Array Test System at the Lord's Bridge Observatory

ELOY DE LERA ACEDO describes the major technical challenges of detecting the cosmological signature of the physics of the Universe when the first stars began the reionisation of the primaeval intergalactic neutral hydrogen.

The Hydrogen Epoch of Re-ionisation Array (HERA) is currently being constructed in the flat semi-desert lands of the Karoo reserve in South Africa. HERA has the objective of making the statistical detection of the power spectrum of neutral hydrogen radiation at the cosmic epoch when the very first stars were born. If successful, HERA will be the first instrument capable of looking back to this key cosmological era. In addition, it has recently been announced that HERA will be a new precursor for the Square Kilometre Array (SKA), meaning a telescope located at an SKA site which will be used as a testbed for the design and development of SKA-related science and technology.

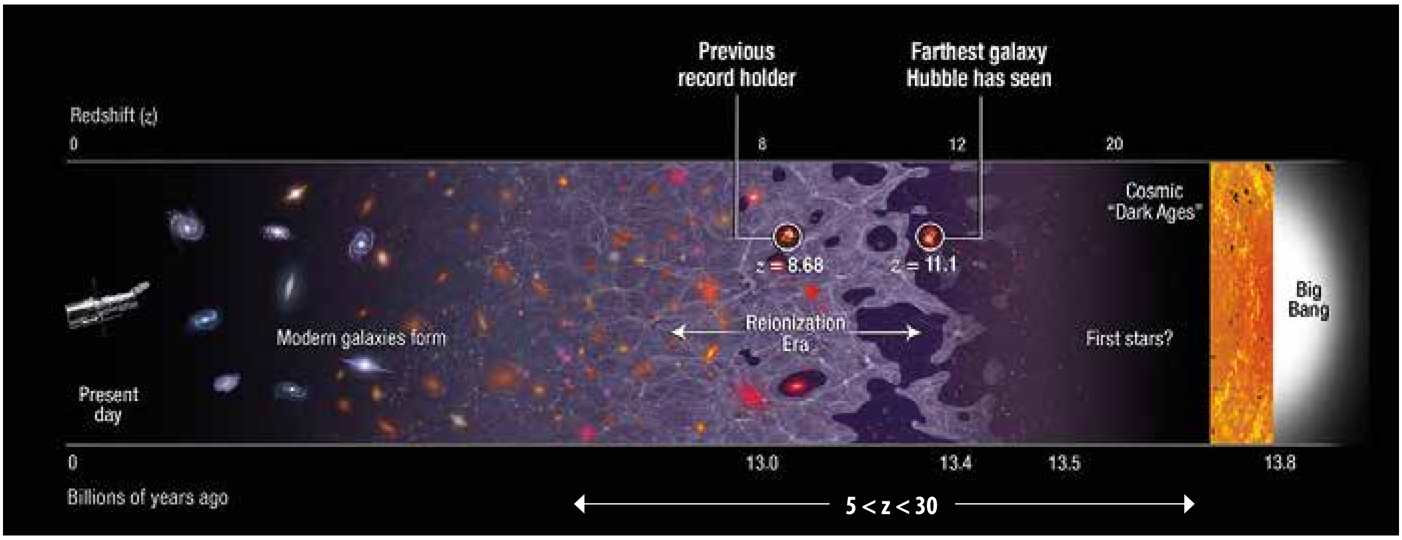
The Big Bang model for the origin and initial evolution of the Universe is by now a very well established research field. At late times, the evolution of galaxies, stars and other celestial objects is becoming much better understood. Less is known, however, about the intervening period, from about 370,000 to 1 billion years after the Big Bang. During this period the Universe transitioned from a neutral cooling gas consisting of about 75% primordial hydrogen and 25% helium to become the realm of the cosmic objects that we now observe from the Earth.

In its earliest phases, the Universe was filled with a fully ionized hydrogen-helium plasma. As this plasma cooled below a temperature of about 4,000 K, when the Universe was about 370,000 years old, an epoch known as the epoch of recombination, electrons and protons combined to form a gas of neutral hydrogen. This neutral matter clumped together under gravity and collapsed to form the first stars and galaxies, a period often referred to as the Cosmic Dawn. The first massive stars emitted intense ultraviolet radiation which heated and reionised the diffuse neutral hydrogen at an epoch referred to as the Epoch of Re-ionization, or EoR (Figure 1).

Probing these epochs, the 'dark ages' before the first stars and galaxies formed, through the cosmic re-ionization epoch and the appearance of first new light in the Universe, is one of the great frontier challenges in astrophysical cosmology. The key to unlocking what happened is to observe neutral hydrogen through this period of re-ionisation. Neutral hydrogen can be observed at a radio wavelength of 21 cm and by observing it at low radio frequencies we can detect directly the highly redshifted radio emission (and absorption) from the gas clouds that were the raw material that formed the first luminous cosmic structures. The huge challenge is that the 21 cm line of neutral hydrogen is a highly forbidden hyperfine transition, with a spontaneous transition probability of only once per ten million years per hydrogen atom and so the signal is so weak that it has not yet been detected, despite considerable efforts on the part of the radio astronomers. HERA is designed to have the sensitivity to make this detection.

HERA will consist of up to 350 14m antennas which can detect radio waves in a frequency band as broad as 50-250 MHz, corresponding to neutral hydrogen in the redshift range roughly $6 < z < 30$. HERA is a US National Science Foundation (NSF) project, in partnership with an international consortium of universities[1]. Researchers at the Cavendish Laboratory are designing the broadband feeds of the array to achieve a wider bandwidth in addition to greater sensitivity. They are also designing the radio frequency receivers and a science simulator for the telescope, as well as being involved in the early processing of observational data from the current 19-dish system at the Karoo (Figure 2). The Cambridge team has recently built a 3-dish HERA prototype (Figure 3) at the Mullard Radio Astronomy Observatory (MRAO) at Lord's Bridge, south-west of Cambridge.

These types of test systems are crucial for the re-ionization experiments. The effect of the much brighter foregrounds that bury the cosmological signal, about 10^5 times brighter than the cosmic signal, call for a superb design and understanding of the instrument's response to both the cosmological signal and to unwanted foreground signals. The particular way in which HERA will attempt the detection of the re-ionization signal is through the so-called 'EoR window' and the foreground avoidance technique relies on an instrument design with a very specific transfer function in the time-domain. It is therefore of great importance for the design of the instrument to characterize its temporal and spectral response, to compare this to simulated data and to feed this information back to the design and optimization process as well as to



the calibration routines. With our 3-dish system we can study the effects of electromagnetic interactions between the dish and the feed, between adjacent feeds and also the influence of fabrication and construction tolerances on the system's performance.

As shown in Figure 4 we have already been able to compare the response of one of the dishes to a control signal injected at the terminals of the feed covering the whole frequency band with our predictions based on numerical simulations. Our team of technicians at Lord's Bridge and here at the Cavendish will now proceed to finalize the construction of the other 2 dishes to perform more advanced tests, as well as measurements of the spatial response of the dishes using astronomical sources and artificial sources such as satellites or drones flying over the field of view of the HERA test system. Furthermore, the collecting area of this system will allow it to be used for other projects in the near future, such as the search for transient events in the northern sky using a fast digital back end.

HERA will not only attempt to make the first detection of the power spectrum signature signal from the epoch of re-ionization but it will also drastically improve technologies and techniques of great relevance for the SKA. The SKA-LOW antenna system will attempt to carry out full tomography of the re-ionization and cosmic dawn periods at the same frequencies as HERA. The SKA will be the first radio telescope to have enough sensitivity to generate images from the re-ionization epoch. A key milestone will be the detection of the power spectrum signal from the 21-cm hydrogen radio emission. HERA will therefore help SKA understand better how to design the hardware and software to probe these fundamental epochs in the evolution of the Universe.

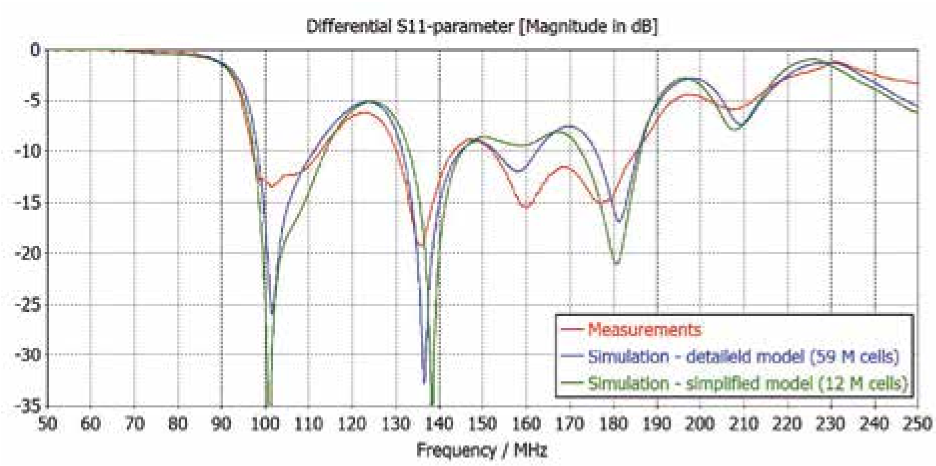
Fig. 1 (top). A brief history of the Universe (Courtesy of NASA and the STScI).

Fig. 2 (left). HERA-19 at the Karoo desert.

Fig. 3 (right). The 3-dish HERA system at Lord's Bridge.

Fig. 4 (bottom). Response of a HERA dish to the injection of a control signal. The vertical axis is in logarithmic units and represents the percentage of returned power with respect to the injected power at the feed. The plot shows a comparison between our measurements and simulations using the software CST and 2 different grids for the computer model with 12 and 59 million cells. As shown, the peaks and troughs as well as the level of returned power show very satisfactory agreement between the results of the experiment and the simulations, validating our computer models.

1. Arizona State University, Brown University, University of California, University of Pennsylvania, University of Washington, Massachusetts Institute of Technology and National Radio Astronomy Observatory, University of Cambridge, Scuola Normale Superiore di Pisa and SKA-South Africa.



"Chance encounter makes amazing ideas possible"

The Maxwell Centre launches a new entrepreneurship programme

YUPAR MYINT and ALEXANDRA HÜNER introduce *impulse*, the new entrepreneurship programme launched under the aegis of the Maxwell Centre. In a dynamic entrepreneurial environment, researchers and aspiring entrepreneurs can meet extraordinary people from various backgrounds - successful entrepreneurs, potential funders, partners and business professionals. The programme will enable researchers to make a connection with them, get the relevant advice and gain access to the resources required in realising their entrepreneurial dreams. The first Module will start in June 2017 at the West Cambridge site.

This initiative was triggered by Richard Friend, the Cavendish Professor, Director of the Maxwell Centre and founder of Cambridge Display Technology, Plastic Logic and Eight19. On the basis of Yupar's more than ten years experience in practical entrepreneurial programmes for scientists and academic entrepreneurs, the vision is to create a programme that will fulfil a unique role in sustaining a strong network of entrepreneurs, practitioners and industry partners, and transferring knowledge, insights and experience to nascent entrepreneurs and researchers.

"The *impulse* programme provides a totally different learning environment for researchers and scientists enabling them to reach their full potential and develop their ideas. The involvement of real business practitioners, with industry knowledge and experience, together with the West Cambridge community sets this programme apart."

Richard Friend

To achieve this vision ***impulse*** has established an impressive advisory board with senior 'role model' entrepreneurs including Chris Abell, David Cleevely, Richard Friend, Hermann Hauser, Andy Hopper, Chris Lowe and Florin Udrea. These successful entrepreneurs/ investors understand the real needs and opportunities available and will advise our budding entrepreneurs in commercialising innovative ideas.

impulse provides a structured learning experience with tailored mentoring for researchers and aspiring entrepreneurs. It serves as a catalyst for entrepreneurship

impulse
MaxwellCentre
for tech innovators

for individuals and organizations. It is about strong action learning and is results driven, the participants bringing their innovative ideas to the table. It acts as a learning vehicle involving prioritising and developing ideas, with a sharp focus on 'high-potential' business cases.

The programme takes place over three months and comprises two three-day intensive residential modules as well as individual assignments. Both on-line mentoring and regular clinics are part of the programme and include discussions with senior business professionals. In this way, participants have more time to develop their ideas with the continued help and advice they need. The programme is run in parallel with their normal work activities – there is considerable flexibility about how the aims of the programme can be achieved.

The programme is targeted at anyone - PhDs, Post-Docs, researchers, early stage entrepreneurs, researchers/engineers/ managers from the corporate sector - who is passionate about developing an entrepreneurial venture in Science and Technology.

The specific benefits for participants are:

- Determine the best business models and marketing strategies for your idea
- Get help and advice for your early stage business development
- Develop commercial skills and apply them in a safe entrepreneurial environment
- Prepare a business proposal and validate it with senior entrepreneurs
- Learn directly from key stakeholders of the Cambridge cluster
- Improve social networking and pitching skills

Yupar in action

"Innovation is a vital ingredient in sustaining the economy. I believe we need to encourage the brightest people with the big ideas, to create a truly inspirational environment and to provide the correct support for those people willing to translate their research results into successful ventures. I fully support the *impulse* programme which will allow the researchers and innovators to test their novel ideas and benefit from the experiences of entrepreneurs, investors and business professionals from the industry."

Hermann Hauser

We welcome opportunities for collaborations with organizations that are actively promoting and supporting Science and Technology entrepreneurs and early stage ventures.

The benefits for the partners are:

- Efficient way of connecting to the Cambridge Cluster and international entrepreneurial networks
- Encourage your participants or employees to think global and be ambitious about their ideas
- Provide them with high value contacts and networks, and top quality feedback
- Prepare the young and talented people to take on new challenges for the future
- Cost saving (instead of organising it yourself)
- Intense programme with a high learning-curve
- Employer friendly programme (only two 3-days workshops with in between individual assignments)
- High visibility of your contribution towards the entrepreneurial society

More details about the application process and all other aspects of the programme can be found at our website:

maxwell.cam.ac.uk/programmes/ impulse

Applications for the first round of the programme are due by **15 May 2017**.

Yupar Myint, Head, and Alexandra Hüner, Coordinator

Email: impulse@maxwell.cam.ac.uk
Telephone: +44 (0)1223 747368

Isaac Physics goes from strength to strength

Since the last issue of CavMag, another 1000 teachers have signing up to use the platform bringing the total to 2680, and the number of students has also doubled over this time to 43158. Our events team have kept up their dizzying schedule of events, with student workshops taking place in Berkhamsted, Radley, Birmingham, Newcastle, Huddersfield, London, Newcastle, Hull, Bury St Edmunds, Sheffield, Ecclesbourne, Norwich and Ipswich. They have also run Continuing Professional Development (CPD) courses for teachers and training for PGSE students, with events in Southampton, Maidstone, Preston, Uxbridge, Bolton, Nottingham, Sheffield, Oxford, London, Leeds and Cambridge, as well as running a stall at the Association of Science Educators conference in January 2017. During that event many teachers visited our stall to express their appreciation for the work being done by the project.

We would also like to welcome our new Widening Participation Fellows:

Robert Firth – a postgraduate researcher at the University of Southampton

Lloyd Cawthorne – a postdoc at the University of Manchester

Jenny Barnes – a College Lecturer at the University of Oxford, continuing the work of **Catherine Hayer**

New Feature – Symbolic Questions

One of the greatest challenges for teachers at A-level, and many Part 1A supervisors as well, is to encourage students to work through questions without substituting in numeric values, but until last year Isaac Physics could only accept numeric answers, leaving us with no way to test this particular skill. That has changed over the past few months as a selection of questions have now been converted to expect a symbolic answer, with more still to come. This has been made possible thanks to the development of a drag-and-drop equation editor which works on desktops, laptops, smartphones and tablets. Why not give it a try by attempting the following question?

https://isaacphysics.org/questions/energy_of_bullet

A bullet of mass m, moving horizontally with speed u, meets a block of wood of mass M travelling along the same line but in the opposite direction with speed U, and remains embedded in it.

Show that the loss of kinetic energy is of the form $kMm/2$ and find the expression for k in terms of u, U, m and M.

Research

With the start of the new school year we've also taken the opportunity to begin research into the effectiveness of Isaac Physics, particularly focussing on the effect of 'active' vs 'passive' hints for our questions. In order to do this we've recruited students from a range of schools, allocated them to the 'active' or 'passive' hint groups and set them questions in line with their lessons. This will continue over this term with the students due to complete a 'Post-test' early next term, which can be compared with their already completed 'Pre-test' results. We hope to be able to publish some results from this research late this year.

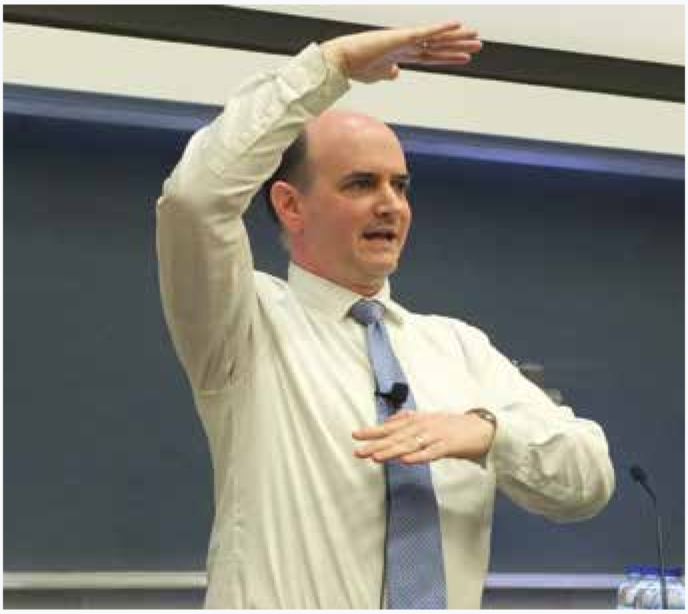
MICHAEL CONTERIO
Member of the Isaac Team

Solar Energies

The 5th Winton Symposium

The 5th Annual Winton Symposium was held at the Cavendish Laboratory on 3rd November 2016 on the topic 'Solar Energies'. RICHARD FRIEND, Director of the Winton Programme for the Physics of Sustainability, introduced the meeting, observing that solar energy generation now offers the cheapest electricity in many parts of the world. The goal of the symposium was to explore the underlying science of light harvesting and how this may lead to further advances in performance. Successful deployment on the global scale requires engagement with the commercial world, a theme that was also touched upon by the speakers.

David King (left), the UK Foreign Secretary's Special Representative for Climate Change, provided an overview of the Paris agreement, and the importance for future human survival of controlling climate change. The agreement has the commitment to limit average global temperature rise to below 2 degrees, preferably less than 1.5 degrees. This target is based on nationally determined contributions, although these as they stand are not sufficient to meet the first commitment, and for these commitments to be reviewable. Even with the best-case scenarios there is a still a 40% chance that the 2-degree target will not be met, at which point the risks begin to increase for significant impact from rising sea levels and crop failures. The positive news is that commercial markets for clean energy are growing rapidly, driven by the feasibility of getting the price below that of fossil fuels. To drive these technologies forward large-scale collaborative projects are required and the Mission Innovate Programme has been established to achieve this. This



has support from twenty-two major governments, each with a commitment to double their governmental clean energy research and development over the next five years, with a total budget of $30 billion a year. In parallel, investment from the private sector has ramped up. For example Bill Gates has provided $1 billion of his own funds to support early stage innovations for clean energy. David ended on an optimistic note - progress can be made by bringing together leading scientists and technologists to turn the biggest risk that humanity faces into the biggest opportunity of our age.

Greg Engel (above) from the University of Chicago explored what we can learn from the design principles adopted in nature for photosynthesis. The goal of the work is not to make plants more efficient, but to learn how they work and then transfer these ideas to molecules and polymers to make more efficient solar cells. Photosynthetic systems comprise a delicate and highly tuned structure that allows the energy from photons absorbed in the light-harvesting pigments to move quickly to the reaction centre where charge separation occurs followed by electron transfer. His group uses femtosecond pulses to explore the coupling between vibronic and electronic states of these systems; chlorobium tepidum, a system that his group have studied, operates at extremely low light levels and has evolved to become extremely efficient. At the heart of this is the Fenna-Mathew-Olsen (FMO) complex that couples the light-harvesting antenna to the reaction centre. Greg's studies show that the excitonic states within FMO are coupled coherently, with surprisingly long dephasing times. The challenge is to engineer systems with long coherence times, and experiments on model molecules are starting to suggest design principles on how to control the spatial relationship of molecules and vibrational modes to increase coherence and thereby produce more efficient devices.

Albert Polman, from the FOM Institute AMOLF in Amsterdam, explained how using the energy of the sun is both a challenge and an opportunity for moving away from fossil fuels. The scale of the problem is enormous with nearly 1% of the land area of the earth needed to provide all our energy needs. As a result it will become one of the largest global industries. The fundamental limit of solar cells is due to the low energy photons not been absorbed and high-energy photons losing energy as they thermalize to the band edge; this is referred to as the Schockley-Queisser limit which for a single junction cell is 34%. In practice cells are not able to reach this limit and there is considerable headroom for improvement. The losses can be described in terms of carrier management, which is mainly a material science problem, and light management, which was the focus of his talk. Several examples were provided of how nanostructures formed by low-cost imprinting can be used to manage the light and modify performance. Absorption can be enhanced which enables thinner devices to be constructed, thereby reducing cost. Metallic structures can be used to combine light scattering and conduction to improve efficiency and tuneable reflection can be achieved to produce coloured solar cells.

Tonio Buonassisi from MIT described technology enablers for large scale photovoltaics with a focus on silicon solar cells. He heads the Photovoltaic Research Laboratory which has activities at MIT in Boston and Singapore. He reiterated the message that we need to cut emissions rapidly, and that the existing pledges are too conservative. We need 4-5 TW of new installed solar energy by 2030 to meet the Intergovernmental Panel on Climate Change (IPCC) targets, whilst existing capacity can only produce 1 TW. To manage this shortfall 22% annual growth will be needed in manufacturing capacity. This will be a difficult task in an industry that has high capital expenditure and low and variable margins. Innovation will thus be needed to drive costs down. One of the most effective ways will be by increasing the efficiency of photovoltaic devices as the majority of material requirements scale inversely with efficiency and half of the system levels costs scale inversely with efficiency. Work in his group has produced higher performance devices through lower defect materials and optimising tandem cells. The process has been aided by using computer simulations with the techniques being applied to other systems such as the perovskites.

Frank Dimroth from the Fraunhofer Institute for Solar Energy Systems in Freiburg explained how climate change is one of the biggest concerns of the day and that working on such a topic was one of the reasons he became a scientist. Although his talk focused on the efficiency of solar cells, he stressed that other aspects such as policy and employment must also be considered. Adding more junctions can improve solar cell efficiency markedly, and III-V semiconductors are an ideal, though expensive, choice as the semiconductor bandgap can be tuned across the solar spectrum by changing the

composition. One of the challenges is to build or bond the different junctions together, and Frank showed recent work using a wafer-wafer bonding technique. A four-junction device has been made in this way, which has reached 46.1% efficiency under high brightness illumination and 43.3% in daylight with a concentrator. This technology has been deployed in South Africa in a 44 MW system. Work is also being conducted on integrating solar energy with hydrogen generation for energy storage, with systems achieving up to 31.5% efficiency. $13 trillion investment in renewable energies is needed by 2030 so there is a bright future for solar energy scientists.

Henry Snaith (above) of the Department of Physics, Oxford University provided an overview of solar cells made with organometallic lead halide perovskite semiconductors. Work from his group has taken these to efficiency levels now approaching those of silicon in the space of 4 years. The big surprise is that these materials can operate in solar cells with much higher levels of impurities than can be tolerated in silicon, and this makes it possible to process them very cheaply.

The best single junction cells now achieve up to 22% efficiency. Early perovskite thin films decomposed at low temperatures but their stability has since been improved through tuning the material composition. One route to commercialisation is to produce a tandem cell with a top layer of perovskite material that absorbs the higher energy, visible spectrum photons on a lower, standard silicon cell that absorbs the infra-red. With the addition of a perovskite layer a significant efficiency increase is possible, and Henry reported exciting progress with these devices.

Jenny Nelson (above), Professor of Physics at Imperial College, focussed on solar cells made out of organic, molecular semiconductors. A study with the Grantham Institute for Climate Change, with which Jenny is affiliated, showed that solar energy is one of the primary technologies which we need to meet climate change targets. The rate of deployment has to increase rapidly and so action has to be taken now. Recent studies show that up to 40% of global power could be provided by solar cells by 2040. This will need increased efforts in research and development as well as learning through manufacturing. The organic materials used in these solar cells can be processed from solution, such as by direct printing, and so offer the opportunity to move to low cost and low energy production. These systems had efficiencies of 2.5% in 2001 and have now reached 11.5% through optimisation of the band gap and band alignments and tuning the microstructure. There is still headroom for improvement for which it is important to understand the sources of energy loss. Absorbance losses can be minimised through design of the device, which is aided by optical modelling. Charge separation is surprisingly efficient, with recent results indicating the importance of non-classical resonance processes aiding the separation. Other losses lead to reduced voltage, due to absorption edge broadening which can be reduced through the use of small molecules that have less energetic disorder. Non-radiative losses due to charge trapping can occur which can be alleviated by reducing defect levels. To conclude, solar power is a critical component of our future energy needs with both R&D push and policy measures essential to accelerate deployment.

NALIN PATEL AND RICHARD FRIEND

New Appointments

Administrative staff

Irene O'Flynn has been appointed temporary HR Operations and Projects Manager and will be with us until the end of May 2017

Damion Box joined us on 3 October 2016 as our new Departmental Safety Technician/Chemical Safety Officer. He and **Saba Alai** will be based in the new Safety Office; 208 B in Bragg Building.

Kevin Gleeson joined the Stores team in August 2016, taking up the post of Chief Stores Technician.

Petra Kasmanova joined the Research Grants team as their new Administrator in August 2016.

Scott Dell is a new Apprentice in the Workshop.

Katarzyna Targonska-Hadzibabic has joined the Rayleigh Library as Library Assistant

Alex Wynick joined AP as the SKA SDP project Administrator in October 2016.

Yupar Myint is the new Head of the West Cambridge Science and Technology Entrepreneurship Programme based in the Maxwell Centre (see page 20).

Fellowships

We congratulate warmly the following who have recently won research fellowships.

Brice Oliver Demory (AP) Royal Society University Research Fellowship (left)

Sam Stranks (OE) Royal Society University Research Fellowship (right)

Christoph Grosse (NP) Humboldt Fellowship

Giullaume Schweicher (OE) Leverhulme Trust Early Career Fellow

Tao Ding (NP) Leverhulme Trust Early Career Fellowship

Joanna Waldie (SP) Herchel Smith Postdoctoral Fellowship

Sarah Williams (HEP) College Fellowship, Murray Edwards College

Robert Hoye (OE) JRF Magdalene College

Matthew Kenzie (HEP) JRF Clare College

Joseph Paddison, (TCM/QM) JRF Churchill College

William Handley (AP) JRF Gonville and Caius College

News

Valerie Gibson is to receive a Royal Society award for her activities to increase and advance women in science, technology, engineering and maths (STEM).

She is among four individuals and two organisations recognised by the inaugural Royal Society Athena Prize, which celebrates individuals or organisations who have contributed most to the advancement of diversity in STEM in their communities. Val has also been appointed as Chair of the IOP Juno Team.

Jacqui Cole has been awarded a Tier 1 ALCF Data Science Program (ADSP) by the Argonnne Leadership Computing Facility (ACF) for her work on 'Data-Driven Molecular Engineering of Solar-Powered Windows'. Jacqui describes her research on page 14.

TEAM CAVENDISH...

Wednesday, 8th of March

WEAR PURPLE

for International Women's Day

A new and diverse generation of Cavendish physicists

12:30–13:30
Launch over lunch
Andy Parker and Rachael Padman will talk shortly about their new vision for the shared 'Team Cavendish' values
(Pippard lecture theatre)
followed by lunch served in the Foyer

WE WILL BE HANDING OUT CAV LAB CANVAS BAGS & LANYARDS
www.cavinspiringwomen.com

More DIVERSITY = better SCIENCE

17:00–19:00
Prof Meena Upadhyaya
Cancer and Genetics, Cardiff University, will speak about her career and her experience as a champion of women in science

Dr. Thekla Morgenroth,
Psychology, University of Southampton
Expert in affirmative action policies, will discuss
What is affirmative action? What are its positive and negative effects?
How to frame AA policies?

nibbles & drinks

HOW YOU CAN CONTRIBUTE

» Online Giving

The University's Office for Development and Alumni Relations (CUDAR) has made it easier to make donations online to the Department and to two of our special programmes. If you wish to make a donation to the Department, please go to:

campaign.cam.ac.uk/giving/physics

If you wish to support the graduate student programme, please go to:

campaign.cam.ac.uk/giving/physics/graduate-support

If you wish to support our outreach activities, please go to:

campaign.cam.ac.uk/giving/physics/outreach

If you would like your gift to be applied to some other specific aspect of the Development Programme, please contact Andy Parker or Malcolm Longair. The Development portfolio is at:

www.phy.cam.ac.uk/development

» A Gift in Your Will

One very effective way of contributing to the long-term development of the Laboratory's programme is through the provision of a legacy in one's will. This has the beneficial effect that legacies are exempt from tax and so reduce liability for inheritance tax. The University provides advice about how legacies can be written into one's will. Go to: **campaign.cam.ac.uk/how-to-give** and at the bottom of the page there is a pdf file entitled **A Gift in Your Will**.

It is important that, if you wish to support the Cavendish, or some specific aspect of our development programme, your intentions should be spelled out explicitly in your will. We can suggest suitable forms of words to match your intentions. Please contact either Malcolm Longair (**msl1000@cam.ac.uk**) or Gillian Weale (**departmental.administrator@phy.cam.ac.uk**) who can provide confidential advice.

If you would like to discuss how you might contribute to the Cavendish's Development Programme, please contact either **Malcolm Longair (msl1000@cam.ac.uk)** or **Andy Parker (hod@phy.cam.ac.uk)**, who will be very pleased to talk to you confidentially.

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