UNIVERSITY OF CAMBRIDGE

THE WINTON PROGRAMME FOR THE

Physics of Sustainability

ANNUAL REPORT

2019

When the Winton Programme for the Physics of Sustainability was established in 2011, through the donation of £20 million by David Harding, the aim was to fund research that could impact how we manage our fragile ecosystem. Eight years later, the need to understand and find solutions to our depleting resources, increased pollution and global warming is still relevant now more than ever.

The Programme has supported research in a broad range of topics, some with obvious connections to sustainability and others in new directions whose impact we will only know in the future. This report provides an insight into the researchers and their work associated with the Programme this year.

REVIEW

Richard Friend,
Cavendish Professor of Physics

The Winton Programme was set up to provide a decade-long investment in the new physics and related sciences that can bring big changes to the technologies we need for a sustainable future. We have now placed most of our investments, principally in early-stage researchers: the Scholars PhD programme, the Advanced Research Fellows, and new Lecturers. Most recently, we have created two new Harding Lectureships to which Dr Chiara Ciccarelli and Dr Akshay Rao have been appointed. They describe their research in this year's report, and both illustrate the scope for fundamental advances in materials and devices that harvest and use energy. In the area of energy storage, our earlier support for Dr Siân Dutton when she took up her lectureship has allowed her to develop research on batteries, and the Cavendish is now playing an active role in the national Faraday Institution.

It is now more than a decade since David Mackay published "Sustainable Energy: Without the Hot Air". This is the book that set out how to estimate the numbers behind our choices for the generation and use of energy, and shows how these numbers have to add up. Many of us had wonderful conversations with David as he was writing the book here in the Cavendish. Later we were thrilled to see its seminal and global impact. His early death in 2016 took from us a brilliant colleague and friend. David presented very clearly then how we faced uncomfortable choices as we decarbonise our economy. A decade later, the urgency to take action is unchallenged in the UK. This is now enshrined in the 2019 modification to the Climate Change Act that requires net carbon emissions be reduced to zero by 2050. The task is still formidable, but industrialisation at scale has brought wind and solar electricity costs to match fossil fuel generation and electric cars are set to be cheaper than petrol or diesel vehicles by the mid 2020s. Beyond the dreams of even the optimists, costs have fallen by a factor of 10 or so since David published his book. The real excitement is that costs will continue to fall as new science and technologies are brought into play. Remember that Moore's Law for silicon worked for far longer than anyone thought possible.

The Winton Programme has provided a focus for research on materials and energy technologies, both in the Cavendish and across the University. It provided the vision and enabled the funding of the Maxwell Centre. It set 'Energy Efficient Materials' as the Cambridge theme in the Henry Royce Institute for Advanced Materials. The Winton Programme will now play a full role in the University's 'Cambridge Zero' initiative as it gathers momentum.

PROGRAMME UPDATE

Nalin Patel, Programme Manager

Overview

The Winton Programme for the Physics of Sustainability has used a series of schemes to attract new researchers and engage existing ones to develop new areas of research that are broadly related to sustainability. The Winton Advanced Research Fellows and Winton Scholars will now be joined by the appointment of two Harding Lecturers, who will have permanent positions in the Physics Department. The Exchange Programme with the Kavli Energy NanoScience Institute and the Pump Prime awards have been used to support new research directions and connections, with the annual Winton Symposium as a forum for engaging with an even wider community.

People

Two Harding Lectureships have been endowed by the David and Claudia Harding Foundation which is associated with the Winton Programme. The new appointees are Dr Chiara Ciccarelli and Dr Akshay Rao who describe their research later in this report. Both have previously held Winton Advanced Research Fellowships that have enabled them to establish their own independent research groups. These permanent positions will provide a long-term platform for their research.

The latest Winton Advanced Research Fellowship was awarded to Robert-Jan Slager; details of his research on topological materials is provided in this report. He will move into the Maxwell Centre which houses the majority of the Winton Fellows. The space is ideal for developing new connections and collaborations within the Winton community, across the University and beyond.

The eighth cohort of Winton Scholars started in October 2018 with a record 10 appointments made; details of the students can be found on the opposite page. Competition for places remains extremely high with applications from across the globe, all the Scholars this year coming from outside the UK.

Engagement

The Exchange Programme between the Winton Programme and the Kavli Energy NanoScience Institute at the University of California, Berkeley is gaining momentum, with reciprocal exchanges taking place. A joint workshop was held this year at which 27 researchers, including 3 faculty members associated with the Kavli ENSI, came to Cambridge to meet and engage with researchers, details of which can be found in this report.

Three Pump Prime awards were granted this year to seed new activities that are high risk, but if successful could lead to considerable impact. As for previous awards, senior and junior members of the Department have proposed novel projects, many using this opportunity to work with researchers across the University; a summary of the latest projects can be found in the report.

The topic for this year's Winton Symposium is "Quantum Technologies", an area of research that has attracted considerable interest in recent years. This will be an opportunity to engage in a discussion on how these emerging technologies could have an impact and the scientific challenges that need to be overcome. The theme for last year's symposium was Machines, which is described in this report.

WINTON SCHOLARS ARRIVING IN 2018/19 (8TH COHORT)

Ivona Bravic
Supervisor: Dr Bartomeu Monserrat
Theory of Condensed Matter Group
"Development of quantum mechanical computational techniques to study finite temperature optical properties of semiconductors"

Romain Debroux
Supervisor: Professor Mete Atature
Atomic, Mesoscopic and Optical Physics Group
"Quantum networks using strain-engineered silicon-based colour centres in diamond"

Kyle Frohna
Supervisor: Dr Samuel Stranks
Optoelectronics Group
"Mapping the Non-Radiative Recombination Losses of Perovskite Solar Cells in 3-D to Approach the Shockley-Quiesser Limit"

Aoife Gregg
Winton Scholar and NanoDTC student

Angela Harper
Supervisors: Professor Mike Payne and Dr Andrew Morris
Theory of Condensed Matter Group and Department of Chemistry
"Ab Initio Studies of Materials for Lithium and Beyond-Lithium Batteries"

Philippe Schwaller
Supervisor: Dr Alpha Lee
Theory of Condensed Matter Group
"Accelerating chemical discovery and synthesis through data-driven physical models"

Soo Teck See
Supervisor: Dr Akshay Rao
Optoelectronics Group
"Ultrafast Super-resolution Microscopy of 2D semiconductors"

Alexander Sneyd
Supervisors: Professor Richard Friend and Dr Akshay Rao, Optoelectronics Group
"New Ways of Understanding the Photophysics of Singlet Exciton Fission for Photovoltaic Devices"

Sarah Ursel
Supervisor: Professor Henning Sirringhaus
Optoelectronics Group
"Ionic liquid gating based thermoelectric transport measurements. Towards the development of efficient, flexible organic thermoelectric generators"

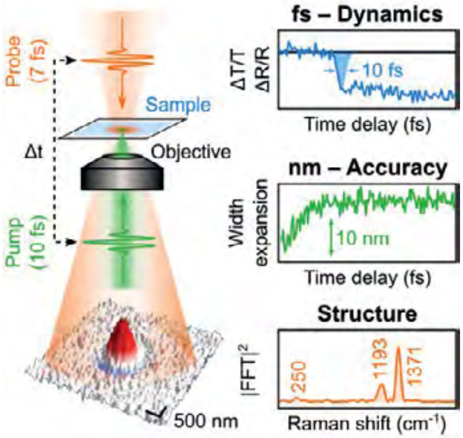
Clara Wanjura
Supervisor: Dr Andreas Nunnenkamp
Atomic, Mesoscopic and Optical Physics Group
"Cavity Optomechanics Beyond Single-Mode Gaussian Steady States"

HARDING LECTURESHIPS

Akshay Rao (Harding Lecturer)

The field of energy materials has emerged as one of the most active research areas in the world today, guided by the long-term vision of combatting climate change and the opportunity to transform the generation and use of energy. An exciting new range of material systems and devices is being studied and developed to meet these challenges. However, there are fundamental differences between well-ordered crystalline materials, such as silicon (Si), which have underpinned the information and communication revolution of the previous decades and the next generation of energy materials and devices, that must be understood to make feasible the coming transformation of energy generation.

These new systems are often disordered, contain complex buried interfaces, are controlled by the flow of various particles and quasiparticles at the nanoscale and have properties that are strongly controlled by vibrational coupling and defects. To unlock the transformational potential of these materials we will need to develop a new experimental toolkit to elucidate their physics over a range of time-scales and length-scales, within complex disordered and dynamic structural and energetic landscapes. Using these insights, we will then need to develop new materials and device architectures to achieve novel functionalities and deliver high efficiencies. This is an extremely challenging task, but



also an extremely exciting one, which opens up opportunities both to push materials beyond their present limits and to explore completely new science.

The vision of my research program is to catalyse a new era in the study of energy materials by elucidating the electronic and structural dynamics and nanoscale transport of charges, excitons, phonons and ions with unprecedented spatial and temporal precision, across a range of energy materials from photovoltaics and LEDs to batteries and thermoelectrics. We seek to provide fundamental insights into the physics of disordered nanoscale materials and use these insights to develop strategies and device concepts that can bring radical new functionalities beyond current physical limits.

Recent examples of our work include the development of fs-transient absorption microscopy which provide sub-10fs time resolution and sub-10nm spatial precision in tracking the dynamics of quasiparticles in semiconductors (see Figure). We have also pioneered the development of a new concept, the Singlet Fission Photon-Multiplier, which could greatly increase the efficiency of conventional Si solar cells. This is now being commercialised by our spin-out company, Cambridge Photon Technology (https://www.cambridgephoton.com/)

Chiara Ciccarelli (Harding Lecturer)

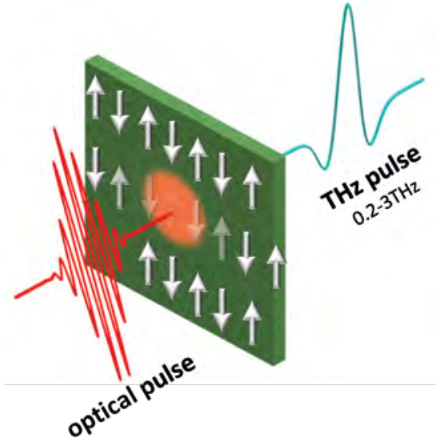
Research in my group focuses on magnetically ordered materials such as ferromagnets and anti-ferromagnets. Our aim is to use new quantum and topological notions in condensed matter to read and write their magnetic state at a speed and with an energy consumption close to the fundamental physical limits. This is important in the context of magnetic storage, where the exponential increase in data production brought by, for example Cloud computing and the Internet of Things, is putting existing data centres under increasing strain.

Ferromagnets are now extensively used for the non-volatile storage of information. Non-volatility also means low energy since the stored information does not need to be continuously refreshed as in other charge-based memories such as DRAM. However, non-volatility and speed have so far been considered incompatible since ferromagnets have typical switching times of 100's of picoseconds. Pushing this limit down to the switching speed of a charge transistor (<5 picoseconds) would allow integration of the memory component to the logic plane, substantially reducing the energy and time wastes during the continuous exchange of information between these two elements.

In order to bring together non-volatility and speed and develop ultra-fast and more energy efficient memories and sensors we are focussing our research on anti-ferromagnets. In these materials, the non-volatility resulting from the internal magnetic ordering is naturally combined with magnetic dynamics that are three orders of magnitude faster than in ferromagnets.

Despite these optimal characteristics, the information stored within the anti-ferromagnetic states is hard to access with macroscopic methods since all these states look identical from the macroscopic point of view, that is, they all have an overall zero magnetisation.

Our approach is to explore new fundamental quantum physical effects that



will allow access to the magnetic order within the anti-ferromagnet at ultra-fast timescales not accessible with ferromagnets. One of the concepts that we are currently exploring is how symmetry breaking can transduce the magnetic ordering within the anti-ferromagnet into an easily readable net electrical signal.

In our past research we have already recognised the importance of symmetry in connecting electrical motion to magnetism [1-3]. We showed that the breaking of inversion symmetry within a ferromagnetic crystal or at an interface leads to the direct conversion of magnons (the quanta of magnetic excitations) into an electrical current [1]. More recently, we pushed this concept even further through collaboration with Prof. Jason Robinson in the Department of Materials Science and Metallurgy and demonstrated the conversion of magnons within a ferromagnet into superconducting currents in an adjacent superconductor [3]. It is now our aim to apply these concepts to anti-ferromagnets in the picosecond time-range.

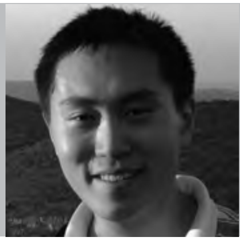
To carry out this research, accessing experimental techniques with the right time resolution is crucial. The Winton Programme has not only been an extremely valuable platform for networking opportunities with both academics and industry, but has also provided me with support to build a time-resolved optical pump-THz probe laboratory at the Maxwell Centre. This facility is now fully operational and shared with Dr. Hannah Joyce at the Department of Engineering and allows us to use both femtosecond optical pulses and THz pulses to both switch and read the anti-ferromagnetic state at controlled temperatures from 3K to 500 K.

[1] Ciccarelli et al., Nature Nanotechnology 10, 50 (2014)
[2] Ciccarelli et al., Nature Physics 12, 855 (2016)
[3] Jeon, Ciccarelli et al, Nature Materials 17, 499 (2018)

Above: Pictorial representation of a typical experiment to read the anti-ferromagnetic state at picosecond timescales. We use a femtosecond optical pulse to drive the anti-ferromagnet out-of-equilibrium. The reestablishment of equilibrium generates a THz electrical response that leads to THz electromagnetic radiation.

RESEARCH

**Alpha Lee and Bartomeu Monserrat,
Winton Advanced Research Fellows**



Materials discovery with computational simulations and machine learning

The Nobel Prize in Chemistry this year was awarded “for the development of lithium-ion batteries”, an overdue tribute to three pioneers whose work enabled a plethora of modern technology. Their methodology for discovering those breakthrough materials was, by and large, purely experimental, driven by profound intuitions and some degree of serendipity. However, under the imminent threat of climate change, this traditional trial-and-error methodology is too slow and too costly. The Lee and Monserrat research groups aim to speed up materials discovery via two complimentary approaches.

The first approach is top-down and data-driven, focusing on combining physical principles with machine learning to infer patterns in experimental measurements or simulation data. The Lee group has developed machine learning algorithms that close the design-make-test cycle in molecular materials.

The first stage in materials discovery is proposing materials, hitherto unknown, that are predicted to have favourable molecular properties. The key challenge is that the dataset size in the literature is often small. They develop methods, inspired by condensed matter physics and statistical mechanics, that filter out noise that arises due to having an insufficient number of data points. In collaboration with Pfizer, the algorithm has been applied to drug discovery to predict whether a molecule will activate a particular physiological process. This approach is twice as efficient as the industry standard, and has led to the discovery of new molecules that activate a protein which is thought to be relevant for symptoms of Alzheimer’s disease and schizophrenia.

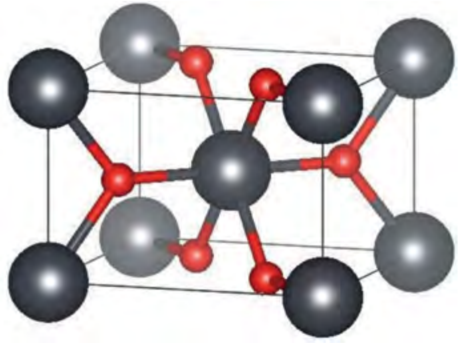


Figure 1: Crystal structure of beta-PbO_2, the first material predicted to exhibit topological order promoted by increasing temperature

Having proposed a promising molecule, the next stage in materials discovery is to make the proposed molecule in the lab. However, the planning of organic synthesis is typically realised by trial-and-error which takes a long time. The Lee group has developed a machine learning algorithm that predicts the outcomes of complex chemical reactions with over 90% accuracy, outperforming trained chemists. The algorithm also shows chemists how to make target compounds, providing the chemical “map” to the desired destination. The algorithm uses tools in pattern recognition to recognise how chemical groups in molecules react, by training the model on millions of reactions published in patents.

The Lee group is currently focused on combining molecular design and reaction prediction algorithms to yield a scientific platform for materials discovery and drug discovery.

The second approach is bottom-up, using quantum mechanics to describe the microscopic behaviour of electrons and nuclei in materials. The Monserrat group develops novel methods to efficiently solve the equations of quantum mechanics with two objectives: first, to help interpret the increasingly complex experiments that our colleagues perform; and second, to guide the discovery process by proposing new phenomena that are yet to be observed in the experimental laboratory. As quantum mechanics is the *theory of everything* for the physical properties of materials, the methods developed by the Monserrat group can be collected in a *virtual laboratory* that finds applications in many areas, for example in optoelectronics for solar cell research or topology for low-power electronics research.

A project led by Antonios Alvertis (Winton Scholar) on organic semiconductors for solar cells has discovered that there is an intimate connection between the localisation range of triplet and singlet excitons and their interaction with the thermal fluctuations of the molecules. These insights provide the prediction that localised excitons are largely temperature independent under realistic operation conditions of solar cells, while delocalised excitons are subject to significant temperature dependences. The experimental group of Dr Akshay Rao (Harding Lecturer) is currently testing these predictions experimentally. Understanding the behaviour of excitations in organic semiconductors in the context of singlet fission is one of the most promising routes towards more efficient solar cells.

Many topological materials support dissipantionless currents that could

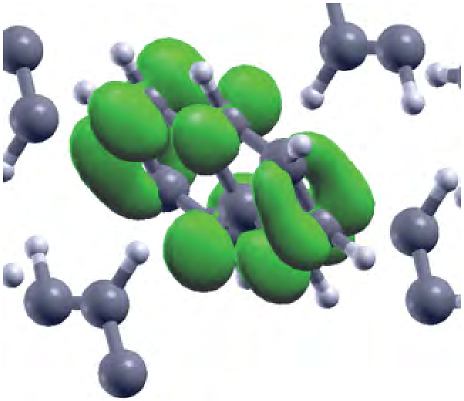


Figure 2: Exciton (green) in naphtalene molecular crystal

form the platform for low power electronics. However, these beneficial properties only exist at extremely low temperatures, precluding applications. We have explained for the first time that temperature destroys topological phenomena with a combination of thermal expansion and electron-phonon coupling. These microscopic insights not only explain all experiments performed to date, but enable us to come up with novel design principles to bypass the detrimental effect of temperature. A project led by Bo Peng (Winton Scholar) and Ivona Bravić (Winton Scholar) has led to the first proposal of a material in which increasing temperature *promotes* rather than suppresses topological phenomena. This represents a paradigm shift when thinking about the interplay between temperature and topology, and shows that temperature is not always detrimental, but in fact can be exploited to design topological materials for technological devices. In collaboration with the experimental group of Prof. Judith Driscoll (Department of Materials Science and Metallurgy) we are currently investigating the realisation of this phenomenon in the laboratory.

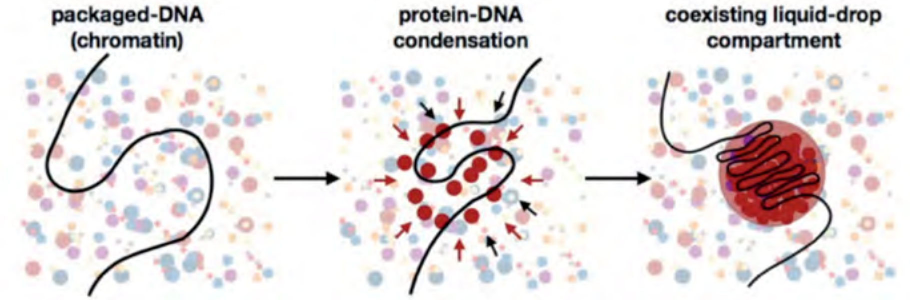
The top-down and bottom-up approaches of the Lee and Monserrat groups are complimentary – the theoretical interpretation of increasingly high-throughput experiments will require advanced data analytics approaches and, conversely using "big data" without theory is blind. The Winton Programme has provided a platform in which to entangle these computational approaches with the experimental research in Cambridge that leads to faster, better, and more impactful science. With this unique environment, the energy challenges that we face are within grasp.

Rosana Collepardo-Guevara,
Winton Advanced Research Fellow

Molecular modelling to understand how the genome works

Genome sequencing has advanced to the point that it can now be used as a routine tool. The challenge has moved to interpreting our genome - finding out how it functions. To answer this, knowledge of the linear sequences of DNA bases is not enough: after all, the different cells in our body (for example skin, heart, liver) contain the same DNA information. In contrast, genomes have intricate 3D spatial organizations that are sensitive to the cell type and cell cycle stage and are intimately linked to function. Not surprisingly, the next breakthrough relies on deciphering (a) how the genome is organized in space and (b) how this organization influences its function.

The work at the Collepardo group aims to address these key open questions by pushing the current limits of realistic computational modelling of genome organization. Guided by experimental observations, physical and chemical information, advanced computer simulation techniques, and the tools of statistical mechanics, we develop powerful multiscale modelling toolkits to investigate the unknown molecular mechanisms that dictate genome folding under varying conditions (for example epigenetic marks, protein binding, DNA breathing), that underlie function.



Recently, we have been investigating a transformative new paradigm for genome function, which suggests that nature uses the physical chemistry of phase separation, liquid-liquid phase separation (LLPS), to control chromatin organisation and gene activity. Like water condensing to form rain drops, the multi-component mixtures of proteins and DNA that exist inside the cell nucleus – where chromatin is stored and expertly organized – can phase-separate into different coexisting liquid drops with differing chemical compositions, resulting in different levels of gene expression (Figure 1).

In this area, our latest simulations reveal the molecular mechanism by which the heterochromatin protein 1 (HP1) undergoes LLPS, how post-translational modifications and protein variants fine-tune the stability of the condensed-liquid domains, how the ability of HP1 variants to enhance the molecular connectivity of the liquid network is positively correlated with their composition inside the condensed liquid phases, and how chromatin condensed inside such domains is driven by entropy (see collepardolab.org).

To assess LLPS both inside the nucleus and in other regions in the cell, we are collaborating with the groups of Professor Tuomas Knowles at the Maxwell Centre, Professors Shankar Balasubramanian and Daan Frenkel in Chemistry, Professor Ernest Laue in Biochemistry, and Professor Julie Ahringer at the Gurdon Institute.

Figure 1, above: Emerging paradigm of chromatin organization via LLPS:

Robert-Jan Slager – Winton Advanced Research Fellow

In a broad sense our research focuses on uncovering universal mathematical structures in the description of phases of matter. A significant part of this endeavour centres around applying ideas from topology to electronic systems. As a result of exciting developments, such topological materials are believed to have significant impact on future technological applications.

Although topology encompasses an established mathematical field, recently it turned out that the essential concepts come to life in the study of electron systems. That is, wave functions may tie collective knots that cannot be disentangled without cutting precisely defined different topological classes. In particular, it was predicted that when certain symmetries are present a novel insulating phase can arise. As in an ordinary insulator, no electricity or heat is conducted in the bulk, but the topological distinction has a profound consequence at the edge. Namely, the non-triviality results in metallic states on the surface that are believed to shape new generation of electronics due to their stability. Moreover, topological materials can give rise to Majorana particles. The possibility of creating such excitations forms a key ingredient in the design of quantum computers. Unlike classical computers that work with classical bits representing 0 or 1, quantum computers use quantum bits that can have any value between 0 and 1, making them infinitely more powerful.

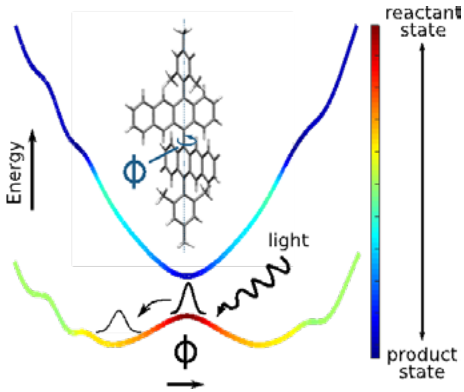
Over the past few years, topological insulators (TIs) have been observed in the laboratory. Finding relevant materials has however, been very much a process of trial-and-error. Within our group, using also insights from competing groups, we have recently discovered that crystal symmetries play an important role. In particular, we found that many more TIs exist and that that they depend on the crystal symmetries in a structured manner [1,2]. The underlying mathematical framework is not only esoterically interesting but also acts as a material guide to find novel TIs systematically. In addition, we have also found that these phases can be further characterized by their responses to defects, a process which in turn can induce different kinds of excitations that have novel (Majorana-like) properties [3,4].

With these new insights, our research will centre around exploring these new phases and their properties in a variety of systems to foster a conceptual basis to propose radically novel future technologies. This is not only anticipated to result in topological material predictions, but also new, experimentally testable phenomena such as recently explored novel excitations that can be manipulated [5,6].

[1] R.-J. Slager, A. Mesaros, V. Juričić and J Zaanen, Nature Physics 9, 98 (2013).
[2] J. Kruthoff, J. de Boer, J. van Wezel, C.L. Kane, R.-J. Slager, Physical Review X 7, 041069 (2017).
[3] R.-J. Slager, L. Rademaker, J. Zaanen, L. Balents, Physical Review B 92, 085126 (2015).
[4] R.-J. Slager, A. Mesaros, V. Juričić, J. Zaanen, Physical Review B 90, 241403 (2014).
[5] R.-J. Slager, Journal of Physics and Chemistry of Solids 128, 24 (2019).
[6] A. Bouhon, R.-J. Slager, T. Bzdušek, arXiv preprint arXiv:1907.10611.

SCHOLARSHIPS

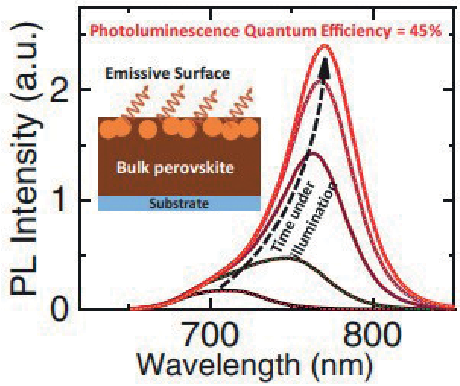
Cohort starting 2016/17



Antonios Alvertis' research focuses on the theoretical understanding of the processes that take place in the early times following the absorption of light from organic molecules. Examples include the transfer of electronic charges and a charge-multiplication process known as singlet fission. Both are critical for light-harvesting applications. However, the interaction between the vibrations of molecules and the motion of electrons has obscured the understanding of such processes. Antonios' research has revealed the precise way in which the electrons and molecular vibrations interact, highlighting the critical role of molecular motion in opening a pathway to the final product of photo-induced reactions. In two recent articles [1,2] the microscopic mechanism of singlet fission and charge transfer is identified, predicting ways of accelerating the former process by 26% and increasing the efficiency of the latter by 20%.

[1] A.M. Alvertis *et al.*, "Non-equilibrium relaxation of hot states in organic semiconductors: impact of mode-selective excitation on charge transfer", The Journal of Chemical Physics, **151**, 084104 (2019)
[2] C. Schnedermann, A. M. Alvertis *et al.*, "A molecular movie of ultrafast singlet fission", Nature Communications, 10:4207 (2019)

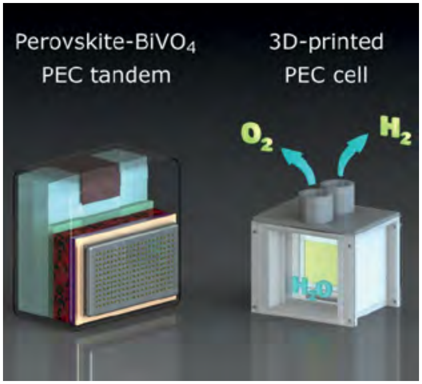
Above: Following light-absorption, vibrations of an organic molecule drive an electronic transition.



Zahra Andaji-Garmaroudi's research is on synthetic perovskites that have been identified as possible, inexpensive base materials for high-efficiency commercial optoelectronic applications.

Her PhD project aims to develop new functional materials, based on lead halide perovskites, for use in light emission and in solar cells. She has explored the changes in solution-processed triple-cation mixed-halide perovskite films under solar-equivalent illumination and found that illumination leads to localized surface sites onto which the charges transfer efficiently leading to high photoluminescence quantum efficiency. She is also studying the impact of doping with different additives on the optoelectronic quality and structural properties of metal halide perovskites.

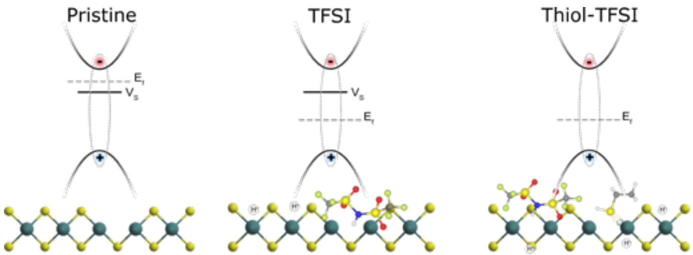
Above: The changes in photophysical properties of mixed-halide perovskite films under solar-equivalent illumination.



Virgil Andrei develops photoelectrochemical (PEC) devices for scalable solar fuel production. His work revolves around the fabrication and characterisation of standalone perovskite-$BiVO_4$ "artificial leaves", which can perform bias-free water splitting and CO_2 reduction under sunlight irradiation. Stabilities of several days are obtained by developing appropriate encapsulation techniques and optimizing the device architecture. Tandem devices of up to 10 cm^2 are characterized in versatile 3D-printed PEC reactors,[1] whereas $BiVO_4$ panels of 300 cm^2 demonstrate the technology's potential for large scale applications.[2] Perovskite photocathodes can perform selective CO_2 reduction at light intensities as low as 0.1 Sun, allowing daylight utilisation from dawn till dusk.[3]

[1] Andrei, V. *et al. Adv. Energy Mater.* **2018**, *8*, 1801403.
[2] Lu, H.; Andrei, V. *et al. Adv. Mater.* **2018**, *30*, 1804033.
[3] Andrei, V. *et al. Nat. Mater.* **2019**. DOI: 10.1038/s41563-019-0501-6.

Above: Depictions of a PEC tandem device and of the modular PEC cell used for the characterisation of larger samples.

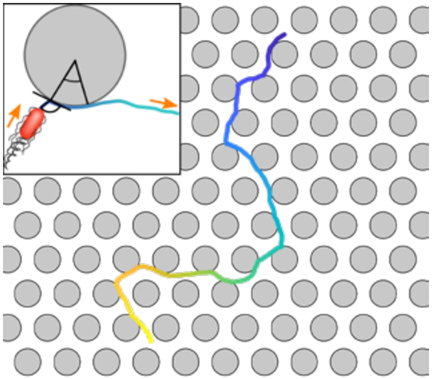


Hope Bretscher studies the photophysics of two-dimensional transition metal dichalcogenides. These van der Waals materials can be exfoliated to the level of a single atomic layer, with properties that are heavily influenced by this reduced dimensionality. However, their experimentally observed properties are greatly influenced by defects within the lattice. Hope is working with chemists in the Rao group to develop and understand chemical treatments that interact with defect states in these materials. These chemical treatments can be used to both passivate the defects, and to tune material properties, opening the door to greater control and functionalization of 2D materials.

Above: In monolayer MoS_2, a sulphur vacancy defect results in an in-gap state, whose role can be enhanced or passivated with different chemical treatments.

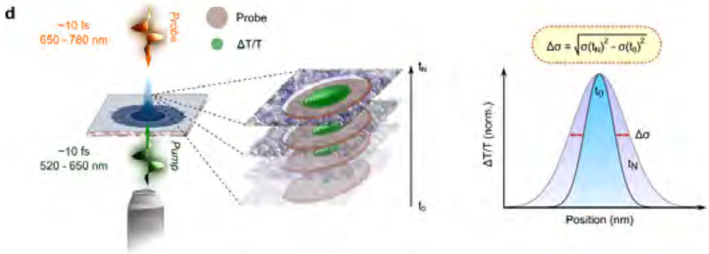
SCHOLARSHIPS

Cohort starting 2016/17



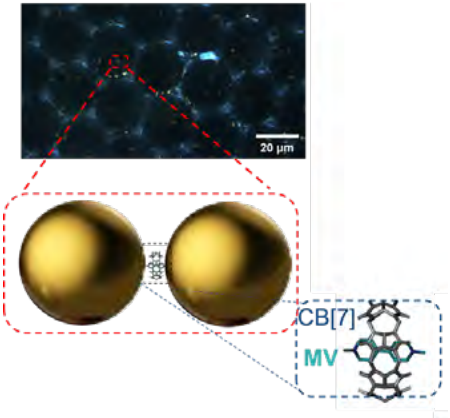
Theresa Jakuszeit's research focuses on understanding the fundamental mechanisms involved in the transport of microorganisms in porous media, which is of interest in biotechnological applications (bioremediation, concentration of algae for harvesting). Bacteria, for example, swim by rotating helical filaments, and navigate complex environments such as soil or human tissue. Hydrodynamic attraction can lead to bacteria accumulating and following surfaces upon collision with obstacles, which has been suggested to impede their motion in complex environments based on gas kinetic models. Depending on the properties of this particle-surface interaction, Theresa showed theoretically and computationally that diffusion can be maintained even at very large densities of the porous medium [Phys. Rev. E 99, 012610]. Using microfluidics to design porous media, she tests experimentally how properties of the medium and the microorganisms influence the macroscopic diffusion.

Above: Illustration of a bacterium interacting with a circular obstacle (inset) and a simulated particle track, which differs remarkably from, e.g., tracks in a dynamical billiard system.



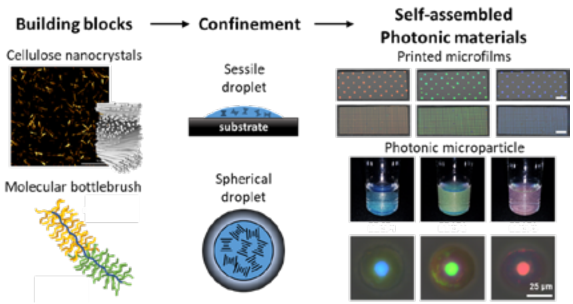
Raj Pandya is investigating energy transport in the form of excitons, charges, phonons, etc in organic and inorganic nanostructures. The efficient migration of energy underlies natural processes (photosynthesis, photo-protection) and many modern optoelectronic devices (LEDs, transistors). Yet, our inability to directly monitor and control energy migration has limited both fundamental understanding and the rational design of materials to meet current demands for clean energy. In his PhD, Raj has developed and applied new tools to directly visualise energy transfer at the nanoscale, discovering a new mechanism based on light-matter couplings that allows for ultrafast, long-range energy migration. Additionally, he has demonstrated how laser pulses can be used to manipulate electronic states within a material such that a desired photoproduct can be achieved from a chemical reaction.

Above: Cartoon outlining the methodology to track energy migration in nanomaterials with ~10 fs time resolution and ~10 nm spatial precision.



Wenting Wang is developing a microfluidic droplet sensing system based on CB[n]-Au aggregates. CB[n] are series of Cucurbit[n]uril molecules which are macrocyclic molecules made of glycoluril (=$C_4H_2N_4O_2$=) monomers linked by methylene bridges (-CH_2-). Single flowing droplets containing analytes can be distinguished by this system. Microfluidic droplets are also used as templates to make soft gels conjugated with CB-Au nanoparticles aggregates to carry out Surface-enhanced Raman Spectroscopy (SERS) sensing, which can filter large molecules by nano-scale pore size of the gels. She is also working on an intelligent toilet project which aims to develop various cheap SERS approaches to detect trace neurotransmitters in urine. One typical approach is to fabricate Au-CB aggregates film on oil/water interface by adjusting the interfacial tension of oil/water. SERS sensing can be achieved on these film substrates either in wet or dry conditions.

Above: Dark-field image of microdroplets containing Au-CB[7] aggregates. MV molecules are fixed in aggregates hotspots by CB[7] molecules.



Tianheng Zhao's research emphasises the importance of geometrical confinement on the result of self-assembly of the photonic materials building blocks. The first building blocks are Cellulose Nanocrystals (CNCs), which are obtained from acid hydrolysis of cellulose, often from filter paper or cotton [1]. The CNCs have a special ability to arrange into a liquid crystalline structure, cholesteric phase, which has an inherent period that is close to visible light wavelengths when dried. By confining the CNCs suspension into minuscule sessile droplets or spherical droplets, the quality of the self-assembly immediately improved and new properties like humidity sensitivity were obtained [2]. The research projects aim to create photonic pigments that are long-lasting, responsive, low-cost and safe for applications in food colourings, cosmetics and biosensors.

[1] R. M. Parker, G. Guidetti, C. A. Williams, T. Zhao, A. Narkevicius, S. Vignolini, B. Frka-Petesic, Adv. Mater. 2018, 30, DOI 10.1002/adma.201704477.
[2] T. H. Zhao, R. M. Parker, C. A. Williams, K. T. P. Lim, B. Frka-Petesic, S. Vignolini, Adv. Funct. Mater. 2018, 1804531, DOI 10.1002/adfm.201804531.

Above: Schematic showing the self-assembly process of two building blocks (Cellulose nanocrystals and bottlebrush block co-polymer) in geometrical confinement to create micro-film arrays and microparticles with photonic responses.

BERKELEY EXCHANGE

The Winton Berkeley Exchange Programme was created to promote the exchange of ideas between the Winton Programme and the Kavli Energy NanoScience Institute (ENSI) at the University of California, Berkeley through exchange placements. The aim is to facilitate complementary research between the programmes that are broadly related to their themes. The third set of awards were made this year and a workshop held in Cambridge to engage a wider range of researchers from the two institutes.

Exchange awards

The Exchange Programme funds exchanges in both directions for up to one year for PhD students, postdoctoral researchers and sabbatical faculty members. This year was the third round of awards with seven granted in total, five visits to Cambridge (UCAM) and two to Berkeley (UCB). A summary of each is described below.

Antonios Alvertis, Graduate Student

Supervisor: Dr Akshay Rao, UCAM
Host: Professor Jeffrey Neaton, UCB

The project "Phonon effects in solid state singlet fission" will investigate the effect that vibrations in solid state structures of organics semiconductors have on single exciton fission, which is a process that can be utilised in solar cells to increase device efficiency.

Chloe Gao, Graduate Student

Supervisor: Professor David Limmer, UCB
Host: Dr Alpha Lee, UCAM

The project "Machine learning sampling of rare nonequilibrium fluctuations" will develop enhanced sampling algorithms to understand transport of matter, energy and charge in nanosystems where microscopic fluctuations become important. This will use an alternative methodology to compute transport coefficients to that Chloe has developed in the Limmer group.

Matt Gilbert, Graduate Student

Supervisor: Professor Alex Zettl, UCB
Host: Professor Ulrich Keyser, UCAM

Matt will bring his expertise in creating structural devices using 2D materials to perform correlated microscopy studies of quantum emission from h-BN defects. He will work with Dr Hannah Stern who previously visited the Ginsberg group at UCB as part of the Exchange Programme.

Stephanie Mack, Graduate Student

Supervisor: Professor Jeffrey Neaton, UCB
Host: Dr Bartomeu Monserrat, UCAM

The first-principles based techniques that Stephanie has utilised to date will be expanded through working with experts in Cambridge in structure prediction and advanced electron-phonon coupling techniques. These techniques will be applied to exploring how electronic and topological features can be manipulated with pressure in materials.

Alex Casalis de Pury, Graduate Student

Supervisor: Professor Jeremy Baumberg, UCAM
Host: Professor Paul Alivisatos, UCB

Alex has formed plasmonic nanogaps by depositing gold (Au) nanoparticles over material up to 10nm in thickness transferred onto flat Au. The techniques developed in Cambridge lead to large field enhancements (up to ~10^4). In this project he will combine work in the Alivisatos group on the modification of Au nanoparticles in graphene liquid cells with plasmonic techniques.

Hsin-Zon Tsai, Postdoctoral Researcher

Supervisor: Professor Michael Crommie, UCB
Host: Professor Stephan Hofmann, UCAM

The Hofmann group has unique experience in growth dynamics and electron microscopy. Hsin-Zon will work closely with the Cambridge team to investigate novel synthesis and patterning of 2D material heterostructures, transition metal dichalcogenides (TMDs) and covalent organic frameworks (COFs) using gas injection equipped scanning electron microscope and image seeding and subsequent propagation of the growth.

Zhixin Alice Ye, Graduate Student

Supervisor: Professor Tsu-Jae King Liu, UCB
Host: Dr Giuliana Di Martino, UCAM

Alice will explore the properties of valence change mechanism (VCM) memristive switches that have high endurance and energy-efficiency. The systems require optimisation and a better understanding of the filament development and dissolution. To study these processes non-destructive optical techniques, developed in the Di Martino group, will be utilised to reveal real-time information about the formation of oxygen vacancies in a model materials stack of TiN/HfO_x/Au nanoparticles.

Exchange Workshop

A joint workshop was held with researchers from the Kavli ENSI and the Winton and Nano Centre for Doctoral Training Programmes. This involved 27 researchers coming to Cambridge including 3 faculty members.

The workshop started with a three-day off site event led by Professor Felix Fischer and Dr Siân Dutton. The first activity involved participants introducing their research project, expertise and equipment to which they have access and their current research challenges. This enabled researchers to get to know each others' research capabilities and prepare for the rest of the workshop that focused on group activities to think about future directions for research and writing and presenting a collaborative project.

A further two days were spent at the Cambridge campus, where a symposium was held with faculty members from Berkeley and Cambridge speaking, followed by an open poster session where all the participants could present their research. Further time was available for Berkeley attendees to meet other researchers as well as see some laboratory facilities, with the aim that some of these may lead to ideas for collaborative projects.

ALUMNI

Breanndan O Conchuir (Winton Scholar, 1st cohort)

Breanndan obtained his PhD in Theoretical Physics in 2015 supervised by Dr Alessio Zaccone. His dissertation focused on applying modern statistical mechanics to describe transport, mechanical response and thermal properties in various soft matter systems relevant for new sustainable technologies. He then worked as an industrial postdoctoral researcher at the University of Erlangen-Nuremberg for two years. Funded by Bayer A.G., Breanndan managed two industrial projects modelling the aggregation of biomolecules in shear flows as well as the ageing of weakly bound colloidal gels. He also led an academic study into the assembly of functionalised nanoparticles.

Since 2017 he has been a Research Staff Member in the chemistry group of IBM Research U.K., where he leads research programmes in the areas of formulation rheology and surface science. His expertise lies in harnessing the latest state-of-the-art High Performance Computing (HPC) hardware to guide industrial chemical research and development activity with in-silico counterparts to laboratory experiments performed by wet-lab scientists. These automated, cloud-accessible, virtual experiments are developed at the interface between data-driven methods and particle-based chemical simulations, and provide both predictions of, and mechanistic insight into, the characteristics of materials and formulated products.

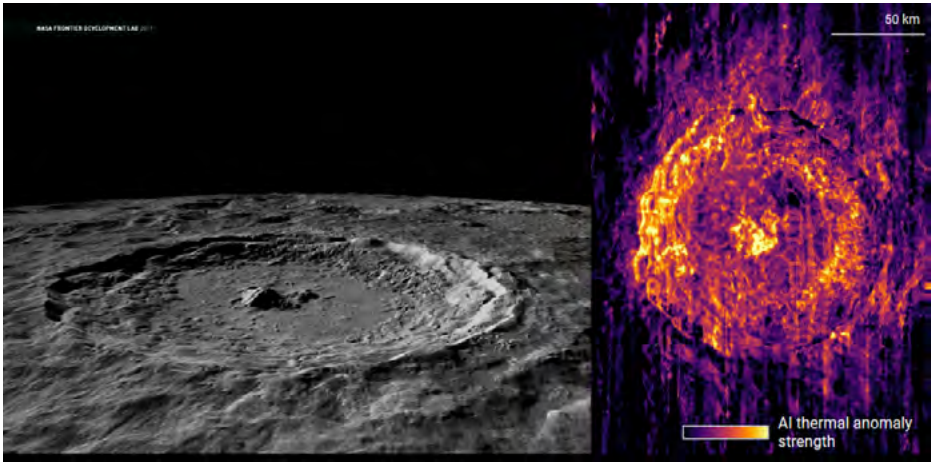


Image of a lunar crater (left) and its AI-generated thermal anomaly map (right)

Jérôme Burelbach (Winton Scholar, 4th cohort)

Jérôme completed his PhD on thermophoresis in the Eiser group in 2018 and then moved to the Technical University of Berlin as a postdoctoral researcher working on the theory of non-equilibrium transport in multi-component systems. More recently he participated in the Frontier Development Lab (FDL), an applied artificial intelligence research accelerator in public-private partnership with NASA in Mountain View, California. FDL applies AI technologies to help solve some of the biggest challenges in space science, such as fighting climate change, improving disaster response, predicting space weather, locating space resources, or identifying meteorites that could hold the key to the history of our universe. As part of the lunar team, he used data fusion and unsupervised machine learning to search for metallic signatures on the surface of the moon.

In particular, the AI-driven approach allowed the team to generate new types of physically-interpretable thermal anomaly maps of the lunar surface. These thermal anomalies potentially indicate the presence of metal resources required for the establishment of a permanent settlement on the moon.

Paromita Mukherjee (Winton Scholar, 4th cohort)

Paromita completed her doctoral research on the magnetic and magnetocaloric properties of complex lanthanide oxides in May 2018. She was supervised by Dr Siân Dutton. She then joined as a Research Associate in the same group on a project funded by the Faraday Institution, UK's independent, electrochemical energy research institute established in 2018.

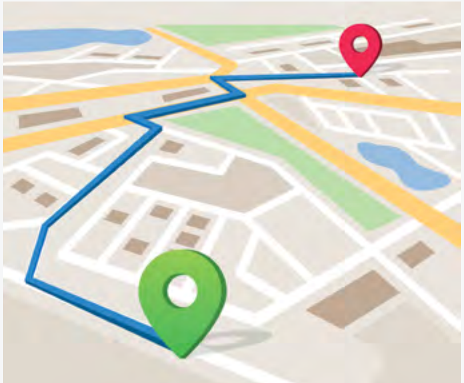
She is investigating the magnetic properties of next generation lithium ion battery cathode materials using a SQUID (Superconducting Quantum Interference Device) [see figure] - an ultra-sensitive magnetometer with capabilities to measure to very low temperatures and high magnetic fields. She aims to combine these laboratory-based measurements with large-scale facility-based techniques such as neutron scattering and muon spectroscopy to gain a fundamental understanding of the degradation mechanisms in lithium ion batteries.

Yago del Valle-Inclan Redondo (Winton Scholar, 4th cohort)

After finishing his doctoral work on the optical control of exciton-polariton condensates, Yago spent a summer in Chicago with the Data Science for Social Good program. Working with the Ministerio de Educacion of El Salvador, he used skills learnt during his PhD as well as new data science techniques to help prevent early student dropout, a significant problem in the country. Yago then moved to Tokyo to work as a JSPS research fellow in the Center for Emergent Matter Science in RIKEN. Here, he continues to work with inorganic semiconductor polariton condensates, on a variety of projects focused on studying the fundamental properties of non-equilibrium quantum mechanics, from the nature of dissipative superfluidity, to the creation of dissipative fractional quantum states of matter.

One project in particular is developing a new way of controlling the potential energy of polaritons, with the aim of turning them into a test-bed for fundamental questions at the interface between non-Hermitian, topological, and non-linear condensate physics, as well as opening the door towards using polaritons for topological quantum computing.

PROGRAMME HIGHLIGHTS



AI learns the language of chemistry to predict how to make medicines

Researchers have designed a machine learning algorithm that predicts the outcome of chemical reactions with 90% accuracy and suggests ways to make complex molecules. The model is more accurate than trained chemists and removes a significant hurdle in drug discovery and materials discovery. The research was led by **Winton Advanced Research Fellow Dr Alpha Lee** and reported in the journals ACS Central Science [5, 9, 1572 (2019)] and Chemical Communications. [DOI: 10.1039/c9cc05122h].

"Our platform is like a GPS for chemistry," said Lee, "It informs chemists whether a reaction is a go or a no-go, and how to navigate reaction routes to make a new molecule."

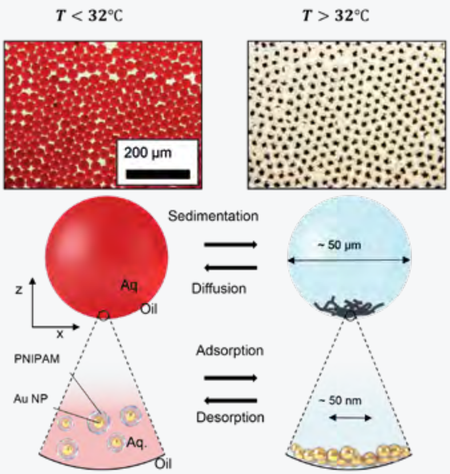
The researchers are currently using this reaction prediction technology to develop a complete platform that closes the design-make-test cycle in molecular discovery: predicting which molecules are promising, ways to make those molecules, and selecting the experiments that are the most informative.

www.cam.ac.uk/research/news/ai-learns-the-language-of-chemistry-to-predict-how-to-make-medicines

Colour-changing artificial 'chameleon skin' powered by nanomachines

In nature, cellular motor proteins move essential materials around cells. Some organisms use these motor proteins to move pigments for adaptive camouflage, such as chameleons.

Winton Scholar Sean Cormier with researchers in the NanoPhotonics Group and the Department of Chemistry has designed microdroplets that mimic the behaviour of these cells using self-assembling particles. Plasmonic gold nanoparticles coated with



poly(*N*-isopropylacrylamide) (pNIPAM), a thermoresponsive material, aggregate when exposed to heat or light. When these particles aggregate in the confines of microdroplets, they sediment into a single cluster and localise at the centre of the droplet. This behaviour generates large changes in material colour and transparency (see figure).

This is a major advance in using artificial nanomaterials to create a dynamic large-scale effect, as seen often with nanomachines in nature. The results were reported in the journal *Advanced Optical Materials* [1900951 (2019)].

Felix Deschler wins €1.7 million ERC starting grant

Winton Advanced Research Fellow, Felix Deschler has been awarded a €1.7 million ERC starting grant to develop highly-luminescent chiral semiconductors with combined properties of ferromagnets and excellent semiconductors, for efficient spin-optoelectronics at room temperature.

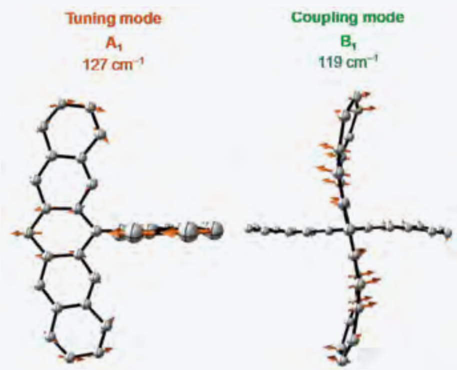
Current magnetic semiconductors are limited by semiconductor quality and operation temperatures. The development of new systems is a scientific challenge due to the required control of spins and physical properties of excited states, while minimizing defects. This ERC project will develop new approaches to control spin and chirality in doped semiconductors. He will employ state-of-the art optical characterization to unravel the fundamental mechanisms of how magnetic moments and light interact and order, with the aim of developing devices with novel functions and lower energy consumption.

Siân Dutton part of a team developing next generation cathodes for Li-ion batteries

Winton affiliated Reader, and former Winton Fellow, Siân Dutton, is part of a team awarded a ~£10 M grant from the Faraday Institution to develop next generation cathodes for Li-ion batteries. The project is led by Prof. Serena Corr from the University of Sheffield with Siân as deputy director and also involves research in Oxford, Lancaster, UCL, ISIS neutron and muon source and the National Physical Laboratory. Other members of the team in Cambridge include Winton affiliated lecturer Hugo Bronstein,

Winton IAB member Judith Driscoll, Norman Fleck, Michael de Volder, and Chris Pickard. The project is aiming to develop next generation cathodes for Li-ion batteries and will explore both existing technologies and new cathode chemistries. Work in Cambridge is focused on experimental and theoretical studies of Li-ion transport at interfaces and optimising electrode design.

Further details can be found at https://faraday.ac.uk/research/lithium-ion/li-ion-cathode-materials/cathode-materials-futurecat/



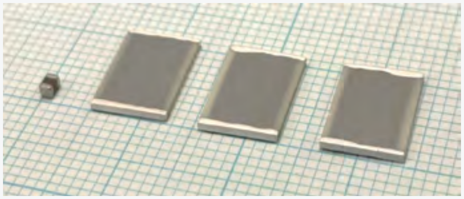
A molecular movie of ultrafast singlet fission

Following light-absorption, an electric charge-multiplication process known as singlet fission can take place in organic molecules. If fully understood, fission can increase solar cell efficiency by a staggering 14%. However, for several years the microscopic molecular motion during this process had remained elusive. In a cross-disciplinary effort, Winton Scholars Antonios Alvertis, Florian Schröder and David Turban, along with Winton Fellows Alex Chin, Akshay Rao and Nicholas Hine, have revealed the full microscopic motion of a molecule during singlet fission, producing the first 'molecular movie' with truly atomistic precision.

Specific molecular motions, such as the ones visualised above, coordinate in a precise manner in order to facilitate fission. Understanding molecular motion during the processes that follow light-absorption opens the path towards the formulation of molecular design rules for their optimisation. Further information can be found in the publication Nature communications [Vol 10, Iss 1, 4207 (2019)].

Survival of the coolest

Winton Scholar Bhasi Nair *et al.* have reported in *Nature* that bespoke multilayer capacitors show electrocaloric temperature changes of 5.5 K when driven with a voltage. By contrast, gadolinium in highly engineered cooling devices shows magnetocaloric temperature changes of 2.5 K. This suggests that better performance could be achieved by a straight swap. Moreover, there would be no need for the bulky and expensive permanent magnets required to drive gadolinium. The picture shows three capacitors with a commercially available capacitor whose electrocaloric effects are an order-of-magnitude smaller.



The research led by Neil Mathur and Xavier Moya in the Cambridge Department of Materials Science was performed in collaboration with scientists at Murata Manufacturing (Japan) and the University of Costa Rica. "Cooling accounts for 20% of the energy budget, making it important to investigate novel approaches," said Mathur.

https://www.nature.com/articles/s41586-019-1634-0

PUMP PRIME

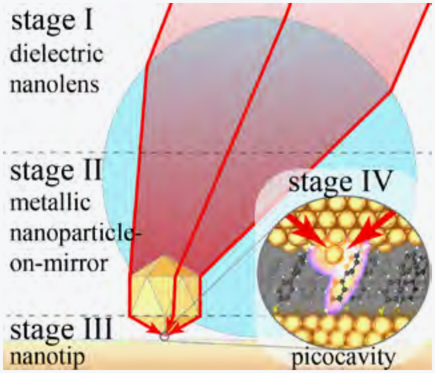
The Winton Pump Prime scheme has been made available to researchers in the Physics Department and collaborators across the University to seed new research activities. These high-risk, high reward projects can receive funding up to £50k. A summary of the latest awards is provided here.

Supershiners for Energy-Efficient Nanophotonic Applications

Dr Bart de Nijs and and Dr Marlous Kamp (Nanophotonics)

Combining refractive and plasmonic lensing in a cascaded nano-optical geometry (see figure) results in extremely efficient SERS sensing requiring mere nanowatts of laser excitation. These novel hybrid optical systems now allow previously inefficient optical processes such as Raman scattering to be used as light sources.

In Raman processes, incident photons can donate phonons to a molecule (Stokes-shift) which can be donated to the next photon (anti-Stokes-shift) resulting in a correlated Stokes-Anti-Stokes photon pair. Such processes are seldom observed, since the phonon lifetime is typically too short to survive between excitations. However, using cascaded nano-optics these processes can now be detected. With the help of the Winton Pump Prime grant we will study



the non-classical behaviour arising in such a system by using very short bursts of intense light to generate both a Stokes and an anti-Stokes photon in each single pulsed excitation and characterise the correlation between the photon pairs. Such a quantum light source would provide numerous advantages: the discrete nature of molecules provides unprecedented reproducibility between devices; the difference in wavelength of the Stokes and anti-Stokes photon allows facile spatial separation; and the narrow spectral width of the emitted photons provides improved coherence lengths over conventional two-level systems.

Automating quantum computers using machine learning

Professor Charles Smith (Semiconductor Physics), Dr Alpha Lee (Theory of Condensed Matter) and Dr Fernando Gonzalez-Zalba (Hitachi Cambridge Laboratory)

Building a large-scale quantum computer requires levels of measurement and tuning that can only be provided by machine control. In this project, we will develop tailored Machine Learning algorithms to automate the calibration of solid-state quantum computing devices to facilitate scaling up to a fully-fledged quantum computer.

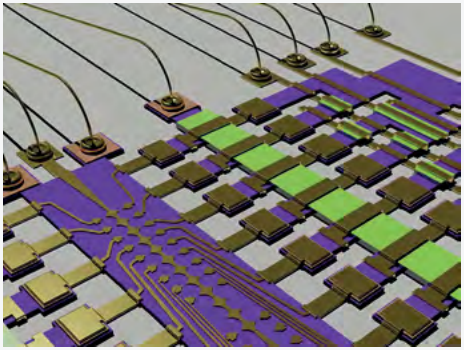
As a test bench for developing tailored Machine Learning (ML) algorithms, we propose to use spin-based solid-state quantum bit (QUBIT) devices because of their potential for high-density integration.

Our approach will be two-fold:

a. GaAs-based spin qubits in lateral quantum dots
b. Silicon-based spin qubit implemented on CMOS transistor nanowires

In particular, silicon spin qubits fulfil all the criteria for being the component of a scalable quantum computer, can be fabricated using CMOS lines [1, 2] and can be integrated with digital electronics [3], making them ideal for large scale integration. GaAs-based qubits are simpler to fabricate and provide a complex multi-dimensional gate space per qubit where ML algorithms can be challenged and can be scaled up for spin and charge cubits.

1. Betz et al Nano Lett. 15 4622 (2015).
2. Maurand et al. Nat. Commun. 7 13575 (2016).
3. R. K. Puddy,. Appl. Phys. Lett. 107 (14), 143501 (2015).

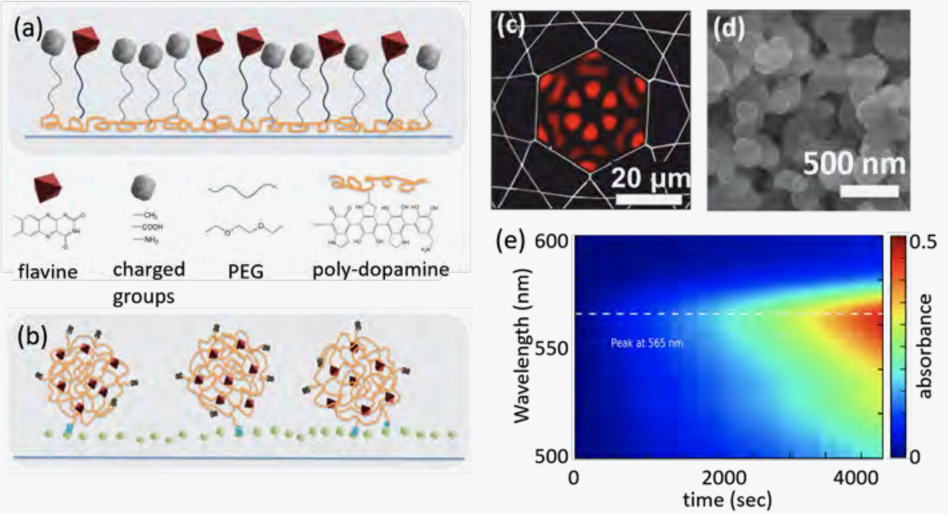


Immobilisation of enzyme-like biocatalysts for sustainable water remediation

Dr Tijmen Euser (Nanophotonics) and Dr Ljiljana Fruk (Department of Chemical Engineering and Biotechnology)

Green catalysts such as flavoenzymes have recently gained momentum in bio-catalytic applications [1]. Unfortunately, their use is currently limited by the high cost of their isolation and purification, as well as their low stability in non-biological environments, making it difficult to transfer these systems to a chemical industry setting. To address these challenges, flavin cofactors (instead of whole enzymes) have recently been studied in catalysis, with varying success. Isolated cofactors are more stable than whole enzymes, but suffer from reduced efficiency and, importantly, cannot be easily recovered from reaction mixtures and reused. The immobilisation of catalysts on solid carriers such as silica colloids can greatly improve their recyclability. However, this process can cause a significant decrease in catalyst activity and selectivity.

In this project, we employ a new approach to study and optimize biocatalysts and use photo-click chemistry [2] to immobilise flavin-dopamine derivatives onto the well-defined internal glass surfaces of silica capillaries and microstructured optical fibres (Fig. 1a-b). Such fibres allow light to be guided at the centre of a microfluidic channel (Fig. 1c), enabling in-situ spectroscopy within tiny (nL per cm fibre) reaction volumes [3]. We will study the photo-triggered oxidation of endocrine disruptors, a class of persistent pollutants encompassing antibiotics, industrial additives and hormones, which are continuously released into water, whose removal is often hindered by a lack of effective strategies. Optofluidic fibres allow light paths of up to several metres in sub-μL sample volumes [3,4], making it possible to detect minute concentrations of these compounds by UV-absorption and fluorescence spectroscopy. We used the optofluidic fibres to demonstrate the efficiency of novel enzyme-like materials towards oxidation of enzyme substrates, and have shown that prepared materials can be switched ON and OFF on demand (5). This success of our collaboration prompted us now to extend the approach further and explore chemical reactions of high interest for greener production of high value chemicals.



Above: (a) direct immobilisation of flavin on silica. (b) FLPDA nanobeads, attached with click-chemistry [2]. (c) waveguide mode in a kagomé-type optofluidic micro-structured fibre [4]. (d) Scanning tunnelling electron micrograph of FLPDA-5 nanobeads. (e) Optically monitored FLPDA-5 - driven photocatalytic conversion of Amplex Red to Resorufin (preliminary data).

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[1] W.P. Dijkman, G. de Gonzalo, A. Mattevi, and M.W. Fraaije, *Flavoprotein oxidases: classification and applications*, Appl. Microbiol. Biotechnol. **97**, 5177-5188 (2013).

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[5] 5. L.Crocker, P. Köhler, P. Bernhard, A. Kerbs, T. Euser, Lj. Fruk, Enzyme-inspired flavin-polydopamine as a biocompatible nanoparticle photocatalyst, Nanoscale Horiz. 2019, Advance Article.

WINTON SYMPOSIUM

The seventh annual Winton Symposium was held on November 1, 2018 at the Cavendish Laboratory on the theme of "Machines: from cosmic to the nanoscale"

Machines for energy conversion and detectors play a crucial role in our society. Key technology drivers now seek to make them more efficient and to operate across different scales. The symposium discussed the chemically powered world of living systems alongside the man-made world of electrically and optically coupled devices with speakers' topics ranging from electric motors to detectors of gravity waves, from nanoscale devices to those spanning kilometres to explore our universe.

Professor Sheila Rowan (above), Director, Institute for Gravitational Research, University of Glasgow, discussed the fundamental physics that can be explored with gravitational wave detectors, the engineering challenges of making these machines with extremely high precision and their applications. Gravitational waves are predicted by general relativity resulting from mass changes that cause extremely small ripples in space-time. The first gravitational waves observed in 2016 were generated in the collision and coalescence of two black holes. The details of the observed oscillations encode information related to this event that took place 1.3 billion light years away.

Professor Mark Kasevich (above) discussed the atom interferometry system he has built in his group in the Physics Department at Stanford University and how this can shed light on the link between gravitation and quantum mechanics. An ensemble of Rubidium atoms is created that is cooled to pico Kelvin temperatures, the atoms are vertically launched into the system and then with light pulses individual atoms are separated. Two ensembles of atoms are thus created which are spatially separated and then are recombined. This is equivalent to the Young's double slit experiment which was first used to explore interference with photons.

Professor Adrian Thomas (above) from the Zoology Department at University of Oxford, discussed flying and demonstrated the design concepts utilised by different birds and the trade offs between efficiency and performance. Experiments performed on airflow show that flyers produce wingtip vortices that lead to areas of down and up lift. By flying in the regions of uplift following flyers can be more energy efficient, with fliers in the 'V' formation being able to be 10-20% more energy efficient. This is commonly seen in the flight of birds; planes can follow this principle but it requires accurate control of flight to maintain position in the vortices. Adrian has established Animal Dynamics Limited that build on his experience with understanding how birds fly to produce high performance drones.

Professor Barrie Mecrow from Newcastle University discussed the limits of performance of current machines and what can we do to push these boundaries. Motors are integral to our energy system with the vast majority of electricity generated using electric machines and more than half of this going to drive electrical motors. He explained how to generate more power and and energy density by going to higher operating speeds and using permanent magnets and superconductors.

Professor Mark Allen from the University of Pennsylvania discussed Micro-electro-mechanical systems (MEMs) technology and their applications. MEMs make use of micro fabrication technologies to make mechanical structures and transducers that are already used in a host of applications from microphones in mobile phones to accelerometers, as well as to pressure and chemical sensors. Mark discussed the move towards using MEMs for medical applications, where as people live longer the focus is on improving the quality of life. He described a number of medical applications where treatment can be greatly augmented by information from implantable devices that could be widely adopted.

Professor Carlos Bustamante is Professor of Chemistry, Molecular and Cell Biology, and Physics at the University of California, Berkeley. His talk explored molecular machines, which operate at energies of the order of kT and are on the nm scale. Cells are neither isotropic nor homogenous and require active motion to function, and not by diffusion alone. These have tiny machine-like devices that convert chemical energy into mechanical forces and torques. He concluded that we are now able to analyse in detail how molecular motors operate, and learn from how they have evolved with the aim of imitating these in the laboratory.

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Cavendish Professor of Physics and Director of the Winton Programme for the Physics of Sustainability, University of Cambridge

David Harding
Chief Executive Officer and Chairman, Winton Capital Management Ltd

Dr Hermann Hauser CBE FRS
Director and Co-Founder, Amadeus Capital Partners

Professor Andy Parker
Head, Department of Physics, University of Cambridge

In attendance:
Professor Lindsay Greer
Head, School of the Physical Sciences, University of Cambridge

PEOPLE

Alexander Sneyd, Angela Harper, Aoife Gregg, Alessio Caciagli, Dr Bart de Nijs, Haralds Abolins, Prof Erika Eiser, Dr Felix Deschler, Dr Ljiljana Fruk

Dr Akshay Rao, Clara Wanjura, Dr Robert-Jan Slager, Dr Alpha Lee, Prof Mete Atatüre, Dr Andreas Nunnenkamp, Sarah Ursel, Dr Chiara Ciccarelli, Romain Debroux

Dr Fernando Gonzalez-Zalba, Dr Hugo Bronstein, Ivona Bravic, Dr Ottavio Croze, Kareem Al Nahas, Dr Rosana Collepardo, Dr Sam Stranks, Timo Neumann, Dr Nalin Patel

Dr Suchitra Sebastian, Dr Tijmen Euser, Evelyn Hamilton, Ezequiel Rodriguez Chiacchio, Alan Bowman, Elaine Kelly, Soo Teck See, Hope Bretscher, Rhys Goodall

Prof Henning Sirringhaus, Jesse Allardice, Diana Sobota, Lauren McKenzie-Sell, Attila Szabó, Philippe Schwaller, Dr Bartomeu Monserrat, Prof Alison Smith, Bhaskaran Nair

Nora Martin, Prof Jason Robinson, Prof Jeremy Baumberg, Dr Giuliana Di Martino, Prof Chris Abell, Prof Neil Mathur, Prof Pietro Cicuta, Prof Sir Richard Friend, Antonios Alvertis

Prof Ulrich Keyser, Raj Pandya, Sam Schott, Sean Cormier, Dr Sebastian Ahnert, Sofia Taylor, Theresa Jakuszeit, Tianheng Zhao, Dr Silvia Vignolini

Iria Pantazi, Virgil Andrei, Wenting Wang, Prof Charles Smith, Sascha Feldmann, Zahra Andaji-Garmaroudi, Jeroen Royakkers, Dominik Hamara, Dr Siân Dutton

Can Kocer, Jannes Gladrow, Dr Marlous Kamp, Prof Erwin Reisner, Dr Rachel Evans, Prof Mike Payne, Dr Claudio Castelnovo, Ture Hinrichsen, Kyle Frohna

THE WINTON PROGRAMME FOR THE

Physics of Sustainability

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