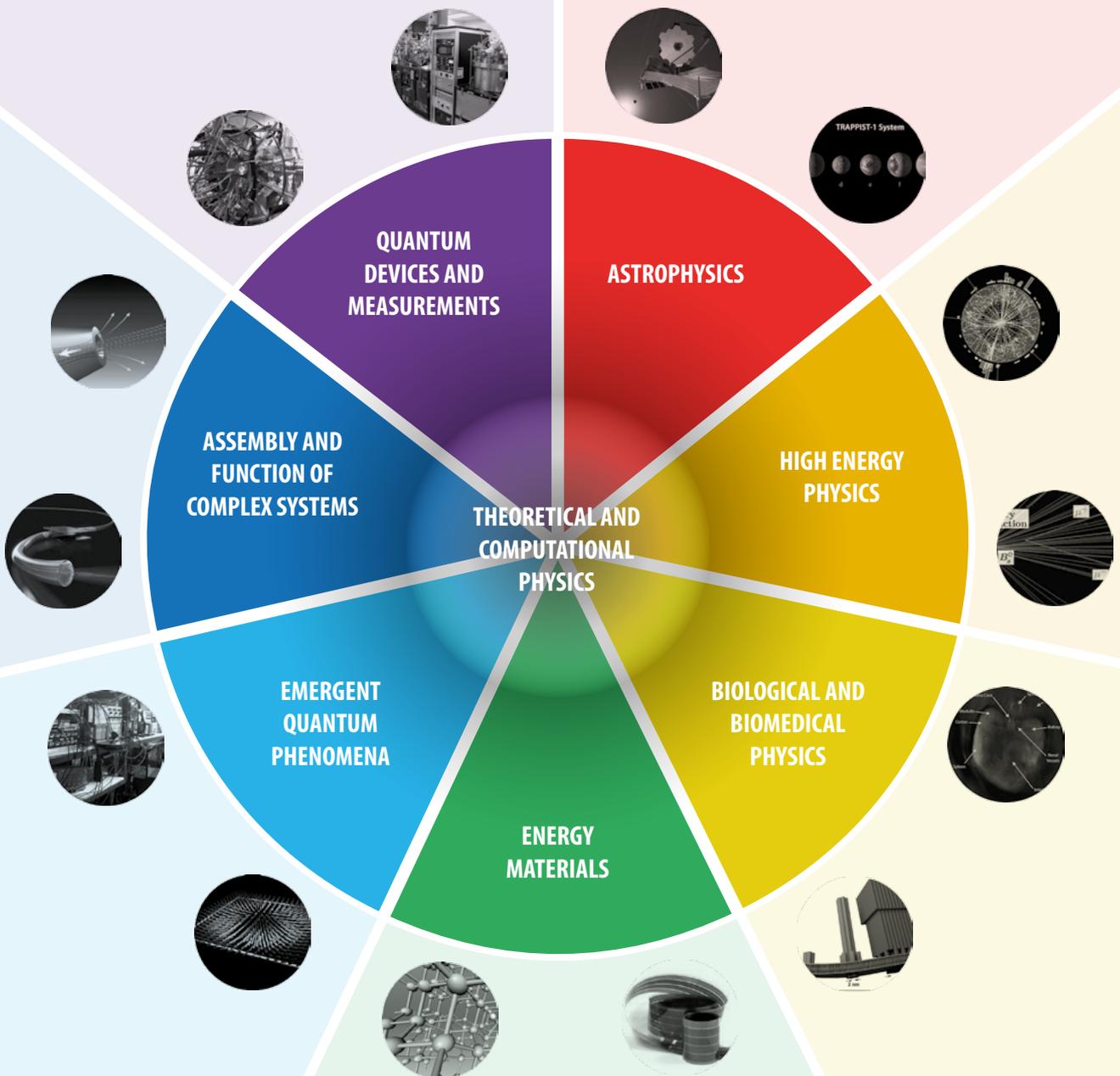




CAVMAG

Special Development Issue



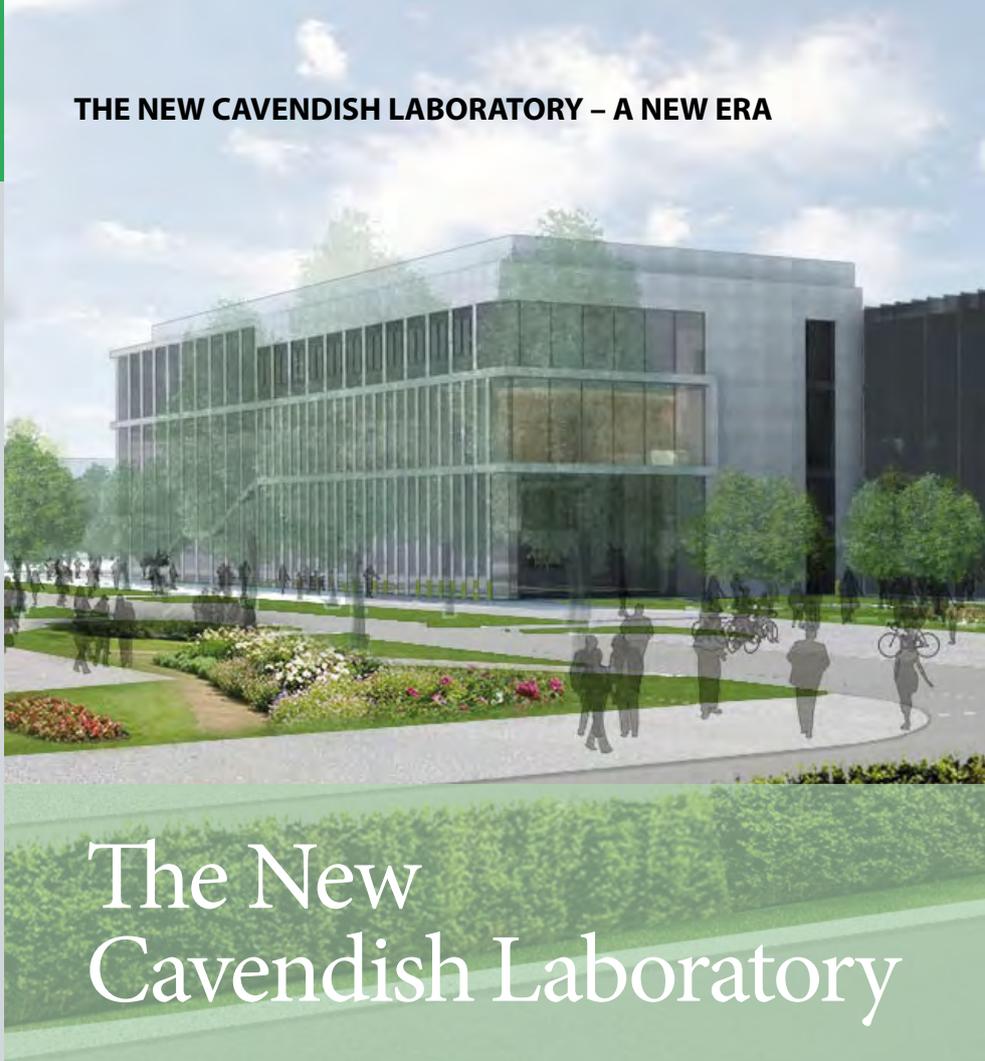
New Cavendish Laboratory Development Programme

This edition of CavMag is somewhat different from the usual combination of science, development, bits of history, personalia and news. This is because we are now getting down to the serious business of planning how the New Cavendish Laboratory will operate when we take occupancy of it in 2022. This edition describes current plans for this next phase of development and the scientific challenges we face. There are many areas where philanthropy can help us achieve these aims - this is a unique opportunity to make a difference. Back to normal at the beginning of 2018.

ANDY PARKER AND MALCOLM LONGAIR

INSIDE

The New Cavendish Laboratory	2
A New and Unique Opportunity for Philanthropic Funding	4
The Science Visions of the Research Themes	6
Astrophysics	8
High Energy Physics	10
Biological and biomedical physics	12
Energy materials	14
Emergent quantum phenomena	16
Assembly and function of complex systems	18
Quantum devices and measurements	20
Pulling it all together - the Role of Theoretical Physics	22
Endowment of Professorships	24
Teaching Initiatives	25
Graduate Students and Research Fellows	26
Outreach and Young People	27
General Equipment Fund	29
Industry and Commerce	30
Future Buildings	31
How you can Contribute	32



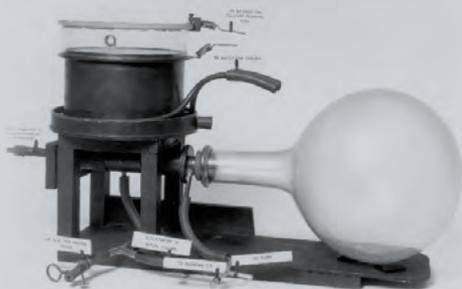
The New Cavendish Laboratory

The core funding for the construction of the New Cavendish Laboratory is now approved and we are looking forward to taking occupancy of the new building in 2021/22. A new strategic plan has been developed for the research and teaching programme, targeted at the many new opportunities which will be exploited when we take up residence. In addition, the New Cavendish will have a national role to play in making available state-of-the-art facilities to the community as a whole.

A New Era

The key message is that **the future will not be just more of the same**, but a genuine renaissance of the way we carry out physics research and achieve our research goals. The spirit of adventure and innovation will be fostered in the Cavendish tradition, but adapted to the new needs of frontier research.

At the heart of the new approach is a more flexible alignment of research activities into research themes, rather than being wholly based upon the traditional group structure. This change of emphasis has been inspired by a number of changes in the nature of contemporary physics research.



The Wilson Cloud Chamber



INTERDISCIPLINARITY

A central feature of current physics research is its cross/inter-disciplinary nature. This has led to numerous research activities which span a number of the themes within the Laboratory and also with other departments in Cambridge and in UK Universities as a whole. The history of physics has shown that many of the most significant advances have come from the discovery space between traditional disciplines. Examples include the symbiosis between cloud physics and particle physics which led to C.T.R. Wilson's invention of the Cloud Chamber (opposite) and the discovery of the double helix structure of the DNA molecule through a combination of biology, X-ray crystallography and theoretical physics (bottom right). Many of the 32 Nobel Prize winners who have been members of the Laboratory adopted this approach to their pioneering researches.

A NATIONAL RESOURCE

The Laboratory has agreed to operate its large-scale facilities as a national resource for the benefit of other UK physics departments. Up to 25% of the use of these facilities will be made available to the community as a whole for their own projects. This brings with it the advantages

of having a stronger case for investing in major facilities in the New Laboratory, as well as fostering new projects with physics departments with which we have not traditionally had scientific collaborations.

INDUSTRIAL COLLABORATION

There is a strong need to enhance our collaborations with industry, building on the initiatives of the Maxwell Centre for cooperation in the basic physics of importance to our industrial partners and the national interest. The Maxwell Centre plans to double the involvement of industry in the physical sciences. The vision for the future physics programme as a whole is that this expansion will apply to all areas of research in the Laboratory.

The research groups will continue to provide the intellectual and experimental backbone of the research activity but seven overarching research themes have been defined which bring together a much wider range of researchers than has been achieved in the past. Members of the new research themes have identified their requirements for people, facilities and infrastructure necessary to maintain the Laboratory's world-leading status. New areas of research where significant

resources are needed to fill important gaps in the research portfolio have been identified.

These evolving changes of direction will in due course impact the undergraduate teaching programme which remains at the heart of the Laboratory's activities.



The half-sized model of the structure of the DNA molecule built for Watson and Crick following its discovery.



A New and Unique Opportunity for Philanthropic Funding

The ambitions of the scientists exceed what is likely to be fundable by government bodies and hence additional resources from industry, philanthropy, independent science funding bodies and other source of support are essential to achieve our goals.

The support needed to implement the new programme spans a very wide range of levels of funding, from modest gifts to support graduate students and enable bright original ideas to be developed speedily to large gifts which will enable major facilities and infrastructure to be provided. These will be pursued aggressively through the research council funding

streams, but it is certain that not all the bright ideas will be supported through this route. Furthermore, the research council funding is hard to obtain for the most demanding and speculative projects and yet these are often the very routes by which the most important advances and innovations are made.

The opportunities for philanthropic funding are unique in that rebuilding an institution such as the Cavendish Laboratory only takes place once per century and, with the opening planned for four years' time, it is timely for donors to consider seriously making significant contributions which will lead to the next major breakthroughs in physics and all its cognate disciplines.

Now is the time to grasp the opportunities for naming areas and facilities within the New Laboratory to honour those donors whose vision of the future importance of fundamental and applied research in physics matches our own.

In the following sections, we outline some the challenges facing the members of the Laboratory and what the outcomes might be. Of course, these exclude the 'unknown unknowns' which result in major changes of direction and paradigm changes for research – the route to discovery is through innovative and bold experiments often outside the mainstream of activity. In parallel with the requirements



of research, there will be **Teaching Initiatives** to enhance the students' experience of learning and understanding physics. Equally important are the essential programmes of **Outreach to Young People and the General Public**. The Laboratory is not funded to carry out these programmes, but we regard these activities as essential to inspire young people and to show the public the enormous benefits to society of investment in physics in all its manifestations.

The Laboratory is committed to supporting **Industry** through a process of **genuine Knowledge Transfer**. This is much more than simply winning research grants from industry but a mutual learning

process between innovative thinkers from academic and industrial backgrounds. It is unarguable that our most important contribution to UK industry is the quality of the research scientists we train in advanced theoretical, computational and experimental physics. Our aim is to make the academic-industrial interface seamless.

Although the New Cavendish project is a very large undertaking, we will need to expand various areas in due course with the construction of **Additional Buildings** as the programme expands through the many new collaborations we envisage with the UK university community and with industry.

The philanthropic aspects of the Development programme will be carried out in collaboration with Cambridge University Development and Alumni Relations (CUDAR) team. The university and industrial collaborations will be developed by the Cavendish's Science Service Unit and the Maxwell Centre. There will be some overlap between these initiatives which are seen as being mutually supportive.

Our development initiatives will be advised by a high level **Development Board**, which will consist of philanthropists who will act as advocates and standard bearers for the New Cavendish, promoting the new vision for physics.

The Science Visions of the Research Themes

As a result of consultation with all academic staff members, the major themes of the research programme have been identified as follows:

- **Astrophysics**
- **High energy physics**
- **Biological and biomedical physics**
- **Energy materials**
- **Emergent quantum phenomena**
- **Assembly and function of complex systems**
- **Quantum devices and measurements**

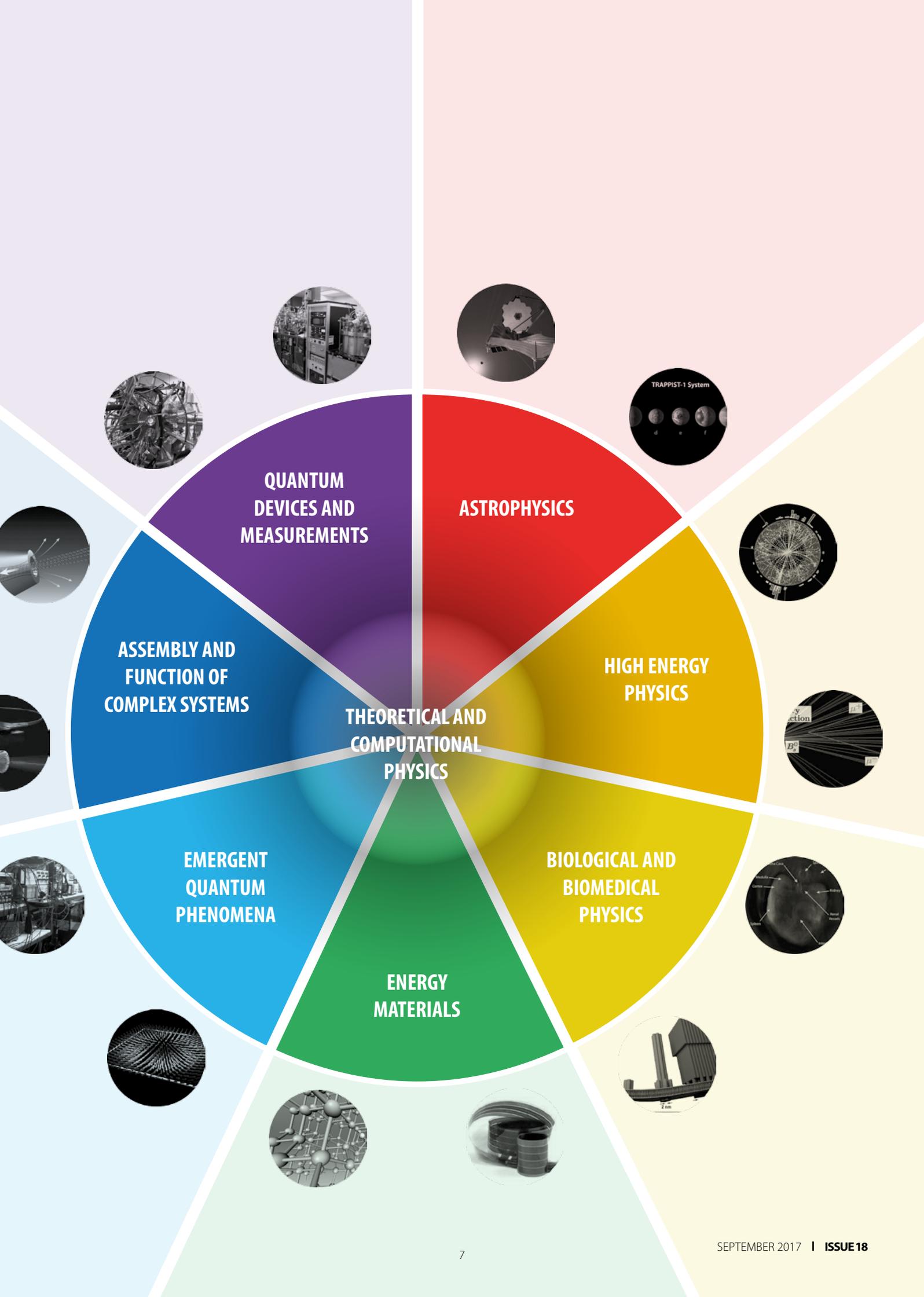
The themes span the full range of research activities being carried out in the Laboratory, as illustrated in the diagram on page 7. While the central core of the research programme is experimental physics, essential theoretical support is provided by theorists in the research groups. Our theorists in astrophysics and high energy physics are embedded within the experimental teams, while those working on condensed matter theory are strongly cross-disciplinary and contribute to most of themes listed above. All carry out fundamental theoretical studies.

Although many of these are familiar titles, the change of approach is that the research programme should not be constrained by traditional group structures, but new associations of cognate interests encouraged within and across themes.

The seven areas are well mapped onto national research priorities. These include the EPSRC Grand Challenge areas, namely: Emergence and Physics Far From Equilibrium; Quantum Physics for New Quantum Technologies; Nanoscale Design of Functional Materials; Understanding the Physics of Life. The highest priority areas in the STFC Particle Physics and Astronomy programmes are well represented in the Laboratory: supporting UK leadership in the technical upgrades at CERN and in the development of the world's largest optical telescope, the European Extremely Large Telescope (E-ELT), the Large Synoptic Survey Telescope (LSST) and establishing the UK lead in the Square Kilometre Array (SKA), for which the UK will provide the international headquarters.

The following pages describe in brief the visions of the research theme members for the future development of their disciplines as well as the types of investment needed to realise them in terms of new positions, facilities, instruments, infrastructure, support and training for graduate students and future buildings.

An introductory paragraph outlines the scope of the research and is followed by specific more technical examples of the new areas to be explored. Many more details can be provided on request, or even better by visiting us and meeting the physicists leading these exciting areas of research.



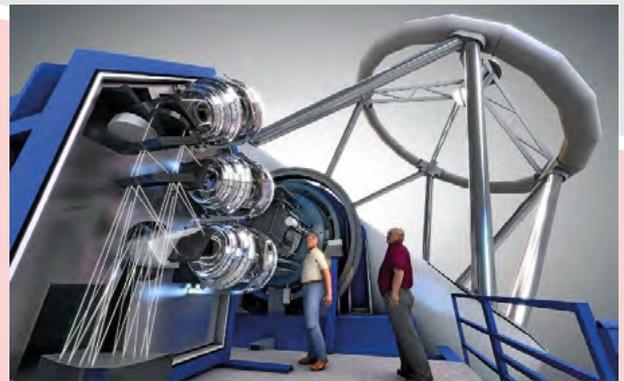
Astrophysics

From the understanding of exoplanets and the origins of life in the Universe, through the study of extreme phenomena involving the physics of black holes to the earliest phases of the Big Bang, astrophysics and cosmology have never had a more exciting agenda. The future programme in Astrophysics and Cosmology encompasses some of the most challenging areas of experimental and theoretical astrophysics, building on the strengths of the Laboratory in these areas. Specifically, we are playing a leading role in the Square Kilometre Array programme with a particular emphasis upon massive data processing. We are designing and building optical-infrared instruments for the next generation of large optical-infrared telescope facilities, including the VLT, E-ELT and the MRO optical interferometer. Theoretical studies in gravitation support the burgeoning fields of gravitational wave astrophysics and cosmic microwave background cosmology.



The frontier research programmes which will be strongly supported are as follows:

1. **Extra-solar planetary research** has resulted in a completely new set of challenges in the areas of planet formation and the study of extra-solar system planetary atmospheres. The programme is developing very rapidly as a joint enterprise between the Laboratory, the Institute of Astronomy, the Chemistry Department and the School of Biological Sciences, creating a major international centre for extra-solar planetary research.
2. **Galaxy evolution:** The galaxy evolution programme exploits our investment and expertise in the most advanced observing facilities such as the Atacama Large Millimetre Array (ALMA), the ESO Very Large Telescope (VLT), the Square Kilometre Array (SKA) pathfinders, the Jansky Very Large Array (JVLA) and the James Webb Space Telescope (JWST). By making cutting-edge observations with these instruments, we aim to understand in detail how galaxies formed from the epoch when the Universe was only about one hundredth of its present age till now. The objective is to observe directly the processes involved in the assembly of galaxies.
3. **Radio cosmology:** We are playing a leading role in the Square Kilometre Array (SKA) to study key problems in astrophysical cosmology, with a particular emphasis upon the epoch of reionisation and searches for molecular emission at the highest redshifts. When galaxies first formed, the intergalactic gas was reionised. The mapping of this process in the early Universe is predicted to be observable at low radio frequencies in the highly redshifted 21-cm line of neutral hydrogen. This investment in the SKA will lead to a long term major role in that project with guaranteed science return in key experiments.
4. **Gravitational Physics:** The discovery of gravitational waves from coalescing black holes in 2015 was a game changer for astronomy and cosmology. There is a major opportunity for Cambridge to exploit and build on its expertise in theoretical gravitational physics and the analysis of experimental data from gravitational wave experiments.



SYNERGIES

1. Big-data, through leading the SKA Science Data Processor design, including Bayesian Analyses of massive data sets
2. Quantum devices and measurements for sensitive receivers for millimetre and submillimetre astronomy
3. Advanced optical design facilities

FUTURE DEVELOPMENTS

1. There are several opportunities for creating **international centres of excellence** in many of these areas. These include **Centres for Extra-solar Planetary Research, for Exascale Astronomy, a JWST data analysis centre** and **an SKA regional centre**, all in collaboration with our colleagues in other Cambridge organisations.
2. The highest priority for the next appointment is a faculty position at professorial level in the area of **Radio Cosmology and the SKA**.
3. To achieve our ambitions in experimental astrophysics, we will need funding of **equipment for experimental astrophysics** in the assembly/laboratory areas in the New Cavendish.
4. The upgrading of the facilities and Laboratories at the Lords' Bridge Radio Observatory will require the construction of new **Microwave Test Facilities**.
5. **Collaborative joint appointments** with the Institute of Astronomy and DAMTP will enable us to exploit Cambridge's strengths in the following areas: radio cosmology and epoch of recombination science, radio instrumentation and technology, exa-scale astronomy, extrasolar planetary research, galaxy evolution and gravitational wave astronomy.

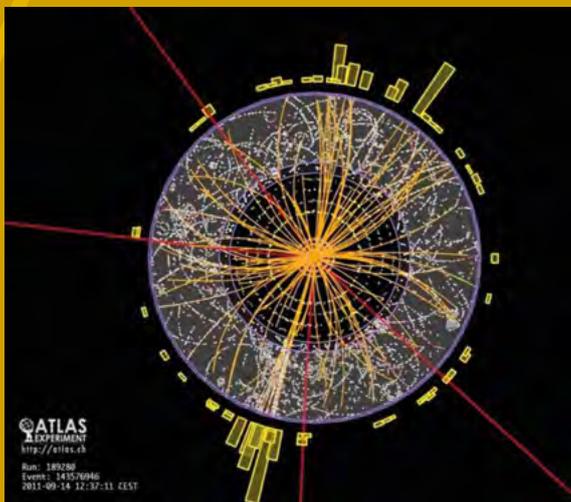
Opposite page, bottom left: The James Webb Space Telescope to be launched in 2018 will be the successor to Hubble Space Telescope.

Above left: The recently discovered TRAPPIST-1 system with seven Earth-like rocky planets orbiting a low mass star. Cavendish researchers played a leading role in the discovery of this system. The planets e, f and g lie within the habitable zone in which liquid water can exist on their surfaces.

Above right: The Multi-Object Optical and Near-infrared Spectrograph (MOONS), being designed by the Astrophysics Group for the ESO Very Large Telescope.

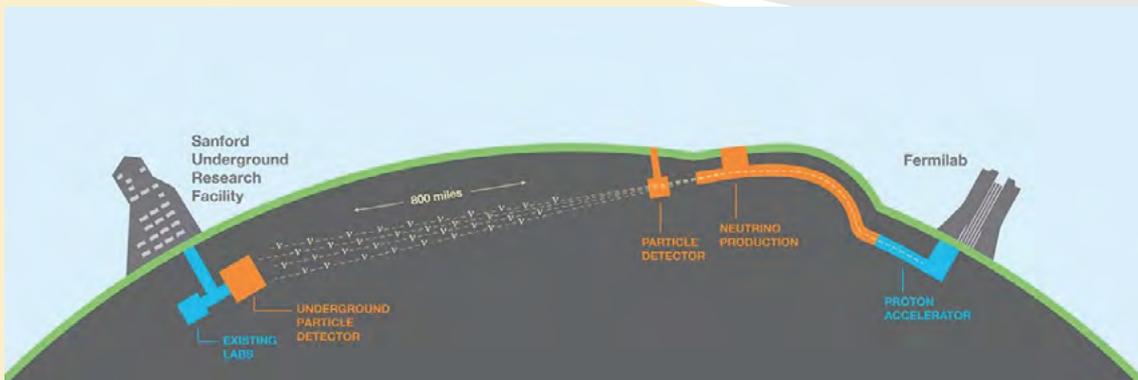
High Energy Physics

The future strategy of the Cambridge High Energy Physics Group is well aligned with internationally agreed priorities in Particle Physics. Experimentally, these are centred on the search for new particles, the discovery of Physics 'Beyond the Standard Model' and the next generation of neutrino experiments. The high energy physicists participate in concepts for the next generation of international particle accelerators. These are supported by a dynamic group in particle theory and phenomenology.



The Group plans to play a leading role in the following major projects:

- 1. Large Hadron Collider (LHC) Physics:** The full exploitation of the LHC, increasing the centre of mass energy of the collisions and the luminosity of the beam in the search for new particles and 'Beyond the Standard Model' Physics. These demanding programmes build upon the remarkable success of the LHC in discovering the Higgs boson and the ability to search for extremely rare events which provide dramatic constraints upon the fundamentals of particle physics.
- 2. Neutrino Physics:** The discovery that neutrinos can change their flavour from electron to muon neutrinos and so on has revitalised neutrino physics. The neutrinos must have finite rest masses and the discovery must involve physics beyond the standard model of particle physics. The Cavendish team is playing a major role in the expansion of the neutrino programme into the Deep Underground Neutrino Experiment (DUNE) in the USA.
- 3. Dark Matter Detection:** Dark Matter comprises about 21% of the critical density of the Universe. Its nature is unknown but a strong candidate is that it is associated with some form of as yet unknown stable massive particle which can be searched for at the LHC and in other experiments. Our approach will involve interdisciplinary research into the direct searches for Dark Matter and the associated theory.
- 4. High Energy Physics Theory and Phenomenology:** The researches of the particle theorists and phenomenologists underpin the findings of the experimental activities and lead to proposals for new experiments and investigations.
- 5. Future Collider Physics:** All cutting-edge particle physics experiments have very long lead times and already plans are being developed for the next generation of particle physics experiments. These include future collider activities at CERN, the Future Circular Collider (FCC) and in Japan, the International Linear Collider (ILC). To play a major role in such projects, there is a need to consolidate and expand the hardware activities to realise a world-leading Technology Centre as part of the New Cavendish Laboratory.



SYNERGIES

1. **Big Data Initiatives.** Massive big data analysis tools are needed to acquire and analyse the vast data rates associated with the particle physics experiments.
2. **Security.** There are many applications of the detector technologies used in High Energy Physics in security applications such as scanning cargos within enclosed containers.
3. **Medical Physics from radio to proton therapy.** High energy physicists collaborate with the University's Oncology Department to find ways of improving the outcomes of these therapeutic techniques and improve medical imaging.

FUTURE DEVELOPMENTS

1. To capitalise upon existing expertise in experimental High Energy Physics, a number of additional posts will be required. These include:
 - a. A **Senior Academic position**, for a physicist with significant hardware expertise and who can lead future hardware activities at the LHC and future colliders.
 - b. Expansion of our silicon detector and electronics expertise with the appointment of a **CMOS engineer and technician**.
 - c. An **academic post** to exploit our existing leadership in **neutrino science** and build up a corresponding hardware activity for the DUNE experiment.
 - d. **Two interdisciplinary academic posts**, one in experiment and one in theory, to expand experimental activities into the direct search for Dark Matter and its theoretical understanding.
2. The **infrastructure and technical capability** for the construction of large HEP detector components using the shared facilities of the New Cavendish Laboratory.

Opposite page, bottom left: An iconic image of a four-muon decay of a Higgs boson detected in the ATLAS experiment at the LHC at CERN.

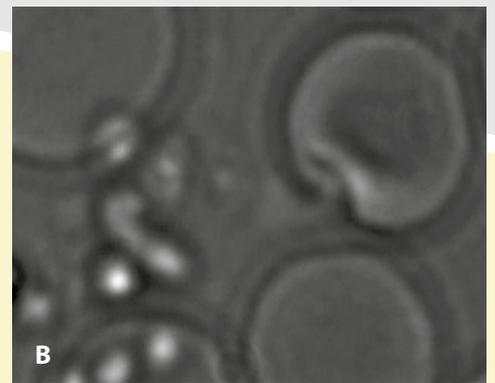
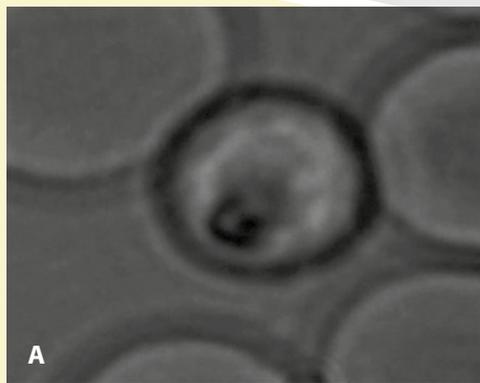
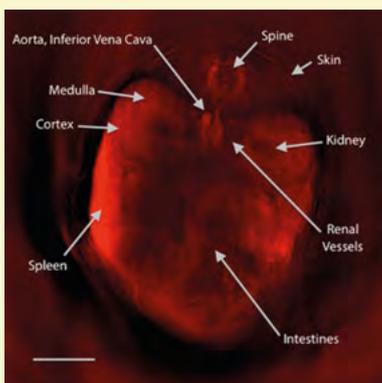
Above: The Deep Underground Neutrino Experiment (DUNE) will search for CP violation in the neutrino sector using a 1,300 kilometre-long beam from Fermilab to the Sanford Underground Research Facility.

Biological and biomedical physics

The interface between the biological and physical sciences will be one of the defining directions of 21st century science. There is growing interest among biologists and clinicians in building closer engagement with physical scientists, and the realisation that many of the key challenges in the life sciences lend themselves to the tools of experimental and theoretical physics. After the breakthroughs by Crick and Watson in the 1950s, interest in biomedical sciences waned until it was regenerated as a major Cavendish theme over the last 15 years. Activities in these areas in the Laboratory now span a very wide range of topics, particularly in the development of new technologies for the biomedical sciences and the theoretical underpinning of these disciplines. The directions of research change quite rapidly with evolving capabilities and priorities and the examples below are just some of the more exciting advances which are currently being actively pursued in the Laboratory.



1. **Spectroscopic imaging modalities:** Spectroscopic imaging modalities to probe cellular structure and function in living human tissues will be developed, with an emphasis on cancer. MultiSpectral Optoacoustic Tomography (MSOT) is emerging as a low-cost tool for clinical imaging and does not require injected substances to create high contrast images.
2. **Studies in cell biology:** Studies in cell biology range from the collective dynamics of bacterial populations and infectious disease transmission, to the dynamics of motile cilia and subcellular processes. An example is the unique automated imaging platform which allows high frame rate videos of rare processes to be obtained with no human intervention. In the example shown opposite-right, this technique has been used to observe how malaria parasites attack cells.
3. Experimental and theoretical research is carried out in the **dynamics of biological molecules and protein self-assembly**. Key topics include protein misfolding, cell adhesion and environmental imaging.
4. **Emergent phenomena in biology:** Emergent phenomena in biology with an emphasis on the regulation of the fate of tissue stem cells in normal and diseased states. These areas have greatly benefitted from the application of the techniques of many-body theory to clinical investigation.
5. A major innovative area of research concerns **transport processes through membranes**, both of biological and “technological” origin using DNA self-assembly (also known as DNA origami), optical trapping, fluorescence microscopy, electrophysiology and microfluidics.
6. Methods are being developed and applied to explore the **genome, epigenome and transcriptome of single cells** to understand better their normal development, and disease processes in human and model organisms.
7. Many of the above are examples of major programmes in **computational image processing and biosensor technologies** which have the capacity to develop into substantial future themes in biomedical research.



SYNERGIES

1. Research in all these areas benefits from close collaboration with cell biologists and clinicians, and all are active in promoting cross-School initiatives at the life sciences interface.
2. The University has strength in all areas of biology, with activities that span the Schools of Biological Sciences and Clinical Medicine.
3. The Cambridge Biomedical Campus continues to develop as a world-leading centre for clinical research, with translational programmes in Stem Cell Biology and Regenerative Medicine, Molecular Therapeutics and Cancer Biology.

Opposite page, bottom left: The Physics of Medicine Building for multidisciplinary research in biological and biomedical physics.

Above left: A blood haemoglobin oxygenation image of large areas of the body acquired using MultiSpectral Optoacoustic Tomography (MSOT).

Above right: High frame rate video has been used to observe how malaria parasites attack cells. Once the parasites are released, they attack healthy cells, puncturing the cell walls as observed in image B.

FUTURE DEVELOPMENTS

1. **Strategic new appointments in Biological and Biomedical Physics** will define a coordinated programme in biological physics, leveraged by expertise within the Laboratory in nano materials, soft matter and theory. These strategic developments will be developed within the context of cognate activities across the Schools, particularly the Schools of Biological Sciences, Clinical Medicine and Technology, and our partner institutions.
2. **Complementary but distinct cross-cutting areas** in which the Cavendish will provide a major impact in the life sciences include:
 - a. The study of basic biological processes, from molecules to cells, tissues and 'communities'.
 - b. The development of enabling technologies based on our expertise in experimental physics in the biological and biomedical sciences.
3. Funding will be sought through **programme grant funding** as well as philanthropic sources for the biomedical sciences. In due course, there are great opportunities for the creation of **Centres for Doctoral Training** in our physics-based approach to the biomedical sciences.

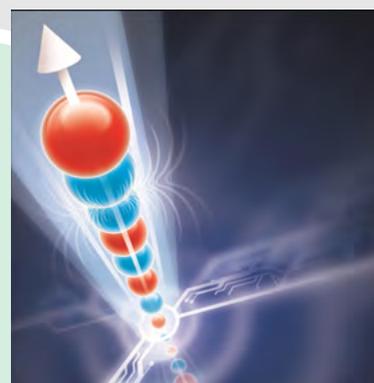
Energy materials

The efficient and sustainable generation, storage, transmission and use of energy is arguably the key challenge facing society in the 21st century, and is one in which physics can play a vital role. For most of the devices and systems that we rely on in our daily lives, such as computers, electricity grids, solar cells or batteries, the efficiency with which these devices use, transmit, convert or store energy is still significantly lower than what is theoretically possible based on established physical limits. In all these areas there are exciting opportunities for developing new advanced energy materials and devices that increase efficiency significantly and in this way reduce the cost and improve the sustainability of energy systems. At the same time this field of physics provides a context for exciting science as it creates opportunities for conceiving and testing new physical principles and paradigms that use energy in novel, more efficient ways. This is a highly interdisciplinary field of physics with close links to chemistry, materials science, engineering and even biology.



The research areas may be classified as follows:

1. **Energy generation:** We are developing new solar cell materials, such as organic and hybrid organic-inorganic (perovskite) semiconductors with the aim of approaching and potentially even beating the so-called Shockley-Queisser efficiency limit, and new materials for thermoelectrics (heat-to-electricity converters) based on conjugated polymers or topological insulators that could reach the efficiency of conventional heat-engines.
2. **Energy Transmission:** In the UK at present about 2% of power is lost in transmission and this is likely to increase in future energy systems that make greater use of renewable sources which will require transmitting power over longer distances. We are searching for new physics that will eventually allow us to realise superconductors at room temperature which will enable essentially lossless transmission of electrical energy over very large distances.
3. **Energy Storage:** To electrify transport and to store the energy generated by fluctuating renewable energy sources, we need better battery materials with higher storage capacity, lower cost and lower embedded energy. Solid state physics and chemistry guided by theoretical simulations open a wide unexplored space of materials for electrochemical energy storage and batteries.
4. **Energy Usage:** The human brain processes information with an energy efficiency that is many orders of magnitude better than that of the best supercomputer. To make computing more energy efficient we are researching new physics paradigms and principles for information processing, such as the field of spintronics that makes use of the electron spin rather than its charge to transmit information. We are also developing more efficient light-emitting diodes based on high bandgap inorganic semiconductors as well as hybrid organic-inorganic semiconductors, that could reduce significantly the amount of energy used for lighting.



SYNERGIES

1. Energy@Cam is a Strategic Research Initiative across the University involving many groups within the Laboratory and many cognate departments.
2. The Cambridge spoke of the Sir Henry Royce Institute (SHRI) is focussed on materials for energy efficient Information and communication technology .
3. The leverage of the Royce Institute and the Winton Investment was crucial in recently winning the EPSRC competition for a National Centre of Excellence in Advanced Materials for Energy Generation and Transmissions, a joint initiative between the Cavendish and the Departments of Chemistry, Materials Science and Electrical Engineering.

FUTURE DEVELOPMENTS

1. **A new post in energy materials** that will take the science in new directions, maintaining and building on the existing critical mass of physical and intellectual infrastructure, with a focus on time-resolved spectroscopy and related areas.
2. **Cross-disciplinary initiatives**, such as joint research programmes and interdisciplinary lectureships that further strengthen interactions between Physics, Chemistry, Materials Science, Engineering and other related disciplines.
3. **Advanced characterisation equipment for novel energy materials**, in particular for studying with atomic resolution the complex structure of interfaces that are crucial to the performance and fundamental understanding of these materials.

Opposite page, bottom left: Strips of organic photocells produced by inkjet printing on a plastic substrate, similar to that used in newspaper printing.

Above left: An X-ray powder diffractometer used in the study of new battery materials.

Above centre: The world's highest field hybrid magnet at the National High Magnetic Field Laboratory, Tallahassee, Florida used by members of the Laboratory in the study of specially designed superconducting materials.

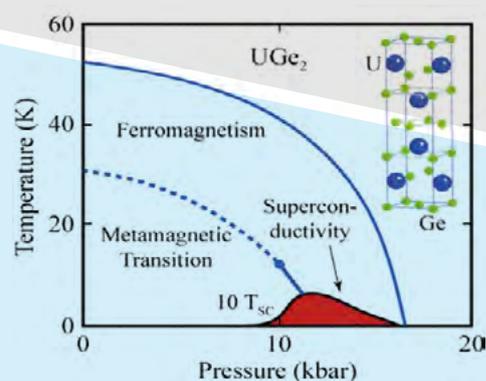
Above right: A schematic diagram of a spintronic shift register, a device in which data are passed along a chain of magnetic memory cells.

Emergent quantum phenomena

How collective, macroscopically observable behaviour emerges from interacting quantum systems is a core theme of physics that continues to produce surprising phenomena and new insights. The classic example of this type of phenomenon is superconductivity, classically associated with the pairing of electrons through interactions mediated by the lattice of the material. But this is only the simplest form of what is referred to as strongly correlated electrons – many other such couplings can take place. These phenomena have the potential to lead to the discovery of new phases of matter which ultimately make their way into applications – for example, the goal of room temperature superconductivity would have extraordinary impact upon society at large. The discovery of qualitatively new phenomena involves the study of matter under very extreme conditions which then inform the design of practical materials for the benefit of society.



1. These **new types of coherent quantum phenomena** involve both correlated electron and magnetic systems. In turn, these may result in unconventional forms of superconductivity, new types of quantum phase transitions and associated structural instabilities. These can lead to quantum functional materials, which may find application, for example in cryogenic refrigeration.
2. **Ultra-cold atomic physics** is now being used to carry out direct experimental programmes targeted at the study of novel phase behaviour in correlated atomic systems. At the lowest temperatures, the materials reach a purely quantum collective state. This enables studies to be made of the quantum behaviour of systems driven far from equilibrium, quench dynamics and turbulence in atomic condensates.
3. These complex areas of strongly correlated systems has led to many **theoretical studies of diverse aspects of quantum many-body systems**. The topics include atomic, electron and light-matter systems, foundational research on frustrated magnetism, topological optical lattices, topological phases of matter and strongly-correlated 1D systems, all topics of intense current interest.
4. The **Advanced Materials Characterisation Suite**, located in the Maxwell Centre, houses state-of-the-art facilities for the structural, electrical and magnetic characterization of complex functional materials, including studies of the behaviour of correlated electrons in novel superconducting materials.



SYNERGIES

1. There are very strong overlaps with the interests of the Quantum Device and Measurements theme.
2. The researchers in this theme have longstanding close collaborations with leading groups in Europe and the USA.

Opposite page, bottom left: A cryogenic facility developed by members of the Laboratory to access very low temperatures from room temperature.

Above left: High temperature furnaces used for the creation of designer materials for low-temperature and battery research.

Above centre: Laboratory for the study of the ultracold atoms and the novel phase behaviour of strongly correlated atomic systems.

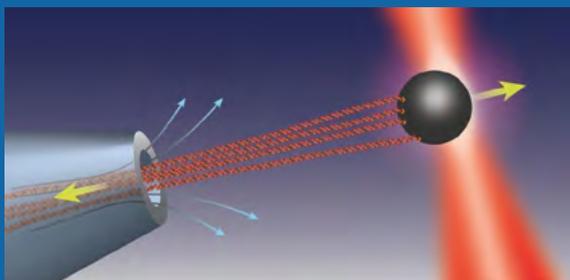
Above right: Emergent quantum phenomena at high pressure and low temperatures in UGe_2 . The phase diagram shows the regions in which the material can be a ferromagnet, a superconductor or a new phase at very low temperatures and very high pressures.

FUTURE DEVELOPMENTS

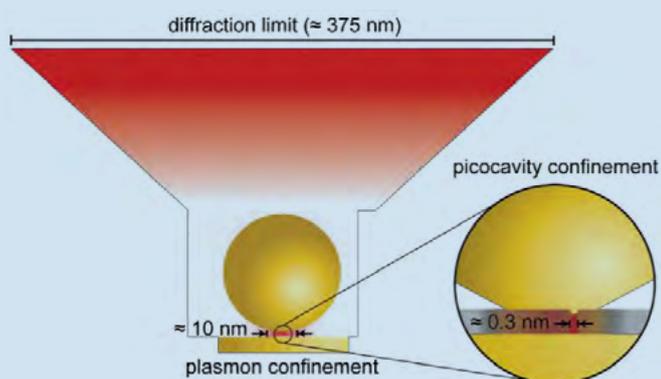
1. Our aim is to maintain our position at the forefront of new research directions and discoveries in these areas, several of which have historically proved hard to foresee. For greater agility in responding to such new developments, we need:
 - a. a **broad expansion of the range of experimental capabilities** that enable accelerated routes to progress in new directions,
 - b. the creation of **two positions** with synergies across these cognate areas. The first post concerns the **dynamic study and manipulation of materials across areas of quantum matter and cold atoms**. The second is in the area of **innovative computational approaches**, which are relevant to new experimental systems of interest to semiconductor physics and cold atoms.
2. There will be **greater integration between research in cold atoms, quantum devices and strongly correlated solids** opening up new possibilities for world-leading activities at the interfaces between these areas and with the potential to establish a highly visible world-leading centre for **novel quantum technologies**.
3. Graduate student training spanning theory and experiment should be supported by a **Centre for Doctoral Training** in this key area for future technologies.

Assembly and function of complex systems

This theme concerns how novel function arises in condensed matter through the assembly of molecular and nano-scale components into complex systems. In contrast to the 'emergent quantum phenomena' theme, the primary focus is on the emergence and control of structural, dynamical and optical behaviour from the nanoscale through the mesoscale to macroscopically observable phenomena. The theme encompasses many aspects of soft matter physics and so is also strongly connected to the physics of biological systems. The theme is strongly interdisciplinary involving many collaborative research programmes with other Departments in the Schools of Physical Sciences, Technology and the Biological Sciences. Some examples of the huge diversity of research and applications are given below.



1. **Nanoscience and nanomachines** are based on a variety of microscopic building blocks and building techniques. These include hybrid colloid particle/DNA materials, thermophoresis & transport, DNA hydrogels as diagnostic tools, micro- and classical rheology experiments & simulations. DNA origami is used in the construction of nanodevices and molecular sensing.
2. The **nanophotonics of atoms, molecules and emitters** in specially designed nano-architectures is a major strength of this theme, as illustrated in the top-left image, opposite.
3. **Hollow fibres are used for photochemistry, sensing, and nano-assembly:** In the example shown in the top-right image, opposite, a 'flying particle' electric field sensor involves an external electric field pushing the optically propelled microparticle out of its equilibrium position, thus modulating the amount of light transmitted through the fibre.
4. Another important area of nanoscience is protein assembly and sensing using **microfluidic techniques**.
5. The Laboratory's traditional strength in **polymer science** is being continued with the study of advanced polymer scaffolds, the theory of soft materials, transport theory, response and random processes. The theme includes functional and optically responsive polymers.
6. Fundamental material interactions and modelling are essential to understand new types of **functional materials**. This is carried out by experimental thermodynamics characterisation and testing interaction theory in polymeric systems. These studies are also related to advanced experiments on energetic materials, in which the Laboratory has a national role.
7. An important field, pioneered by the late Sam Edwards, is the study of **composite and granular materials**. Control of complex materials is achieved through tailored nano- and meso-scale properties using the technique of self-organised criticality. These investigations result in materials by design.



SYNERGIES

1. The bottom-up assembly of functional systems is an area of research involving many staff across the Department, with very significant potential for further coordination and synergy.
2. Collaborations with the Departments of Chemistry and Applied Mathematics and Theoretical Physics are thriving in both experimental and theoretical soft matter.
3. Ongoing collaborations take place with established Centres for Doctoral Training, with the Departments of Engineering, Materials Science and Applied Mathematics and Theoretical Physics.

Opposite, bottom left: Force on DNA in a micropore using optical tweezers formed by pairs of lasers.

Above, top left: Illustration of the cascading coupling of light to localised plasmons to picocavities. Light focussed by a lens is first coupled into the gap underneath the nanoparticle, and then trapped at a single atom protrusion.

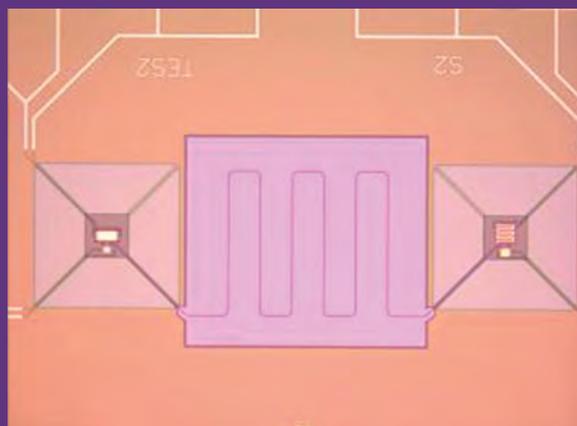
Above, top right: Schematic of a 'flying particle' electric field sensor. An external electric field pushes the optically propelled microparticle out of its equilibrium position, thus modulating the amount of light transmitted through the fibre.

FUTURE DEVELOPMENTS

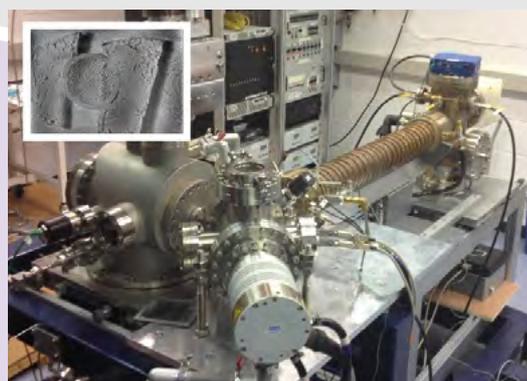
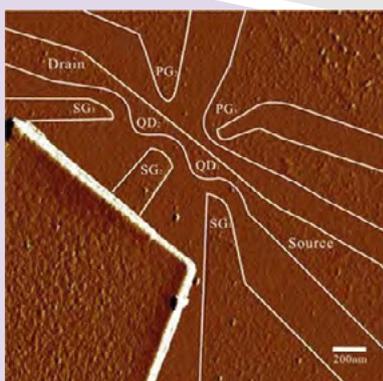
1. The creation of a **Collaborative Centre for the Physics of Nano-systems and Intelligent Nano-Machines**, linking the work of five PIs with relevant activity in this area.
2. The long-term goal is to develop **new approaches to the assembly of functional nanomachinery**, including assembly of quantum emitters into nanostructured photonic environments.
3. **Regeneration of statistical physics, particularly from a theory perspective**, is an underpinning activity for many other areas of research and an important component of our teaching programme. This will be fostered through close links with experiment and a focus on non-equilibrium properties.
4. **Econophysics** in data and information physics builds upon the impact made in this area by the pioneering researches of the **late David MacKay**.
5. **New academic posts in the dynamics of complex materials** will take the field in new directions, building upon and sustaining the existing critical mass.

Quantum devices and measurements

This theme concerns the development of materials, devices and systems in which quantum and spin phenomena can be controlled for technological applications, in other words, to access the quantum behaviour directly at a device level. Although quantum mechanics has been involved in device technologies for many years, the revolution which is taking place is to use the fundamental processes involved in quantum physics directly. These will be the key technology for the present century and will involve new concepts to exploit the many non-intuitive features of quantum systems. The theme spans Quantum Technologies as well as Nanomagnetism and Spintronics. The immediate and longer term future will see developments in the following areas.



1. **Quantum cascade lasers** will be developed as high power THz sources for industrial and medical applications. Graphene-based meta-material devices will find application as THz modulators and detectors.
2. **Single and entangled photon pair sources** will be constructed spanning a range of wavelengths both for quantum computing and for quantum key distribution applications. Another development of basic importance for quantum computing concerns flying QUBIT systems where single electrons are transported from one quantum dot to another using surface acoustic waves.
3. A major goal in the area of semiconductor physics is the development of **radio frequency quantum readout of spin states** in double quantum dot QUBITS in graphene, GaAs, isotopically pure silicon, carbon nanotubes and colloidal gold nanoparticles. The technologies are required for practical quantum computer applications.
4. There is a need for fundamental research on **solid-state quantum optics** combined with emerging quantum-enabled technologies.
5. **Low-noise quantum sensors** will be developed for astrophysical and applied science applications, based on superconducting detectors for the millimetre, submillimetre and infrared regions of the electromagnetic spectrum.
6. In the areas of **Spintronics and Nanomagnetism** there are many opportunities for major innovations in using the spin rather than the charge of the electron as the basic building block. The types of materials and applications will include antiferromagnetic spintronics, organic spintronics, optically-driven domain wall motion in a ferromagnetic semiconductor, piezoelectricity-induced strain control of nanomagnetic devices, biotechnological applications of nanomagnetism, 3-dimensional spintronics and 3-dimensional nanoprinting, and the spin Hall effect.
7. New techniques and instruments will be developed and applied for the study of **nanoscience processes** at surfaces. Helium spin-echo techniques will be used to study the classical to quantum transition in the transport of matter, energy exchange and coupling, and nanoscale-friction. Another ambitious goal is in establishing neutral matter wave microscopy for ultra-sensitive material and device characterisation.



SYNERGIES

1. Spintronics and nanomagnetism is an activity that already spans several of the existing research groups and engages closely with locally-based industrial research, particularly at Hitachi and Toshiba.
2. There is strong overlap with the Device Materials Group in the Department of Materials Science and Metallurgy.
3. The Cambridge Surface Science Forum links initiatives and research programmes across Physics, Chemistry, Materials Science, Engineering and Chemical Engineering.

Opposite, bottom left: An ultra-low-noise quantum detector used for the next generation of astronomical space-borne observatories.

Above, top left: UHV sputtering facility with $<10^{-10}$ torr base pressure and substrate temperatures of -200C to 900C allows a range of materials to be deposited with different stoichiometries.

Above, top centre: An Atomic Force Microscope image of a graphene double quantum dot device.

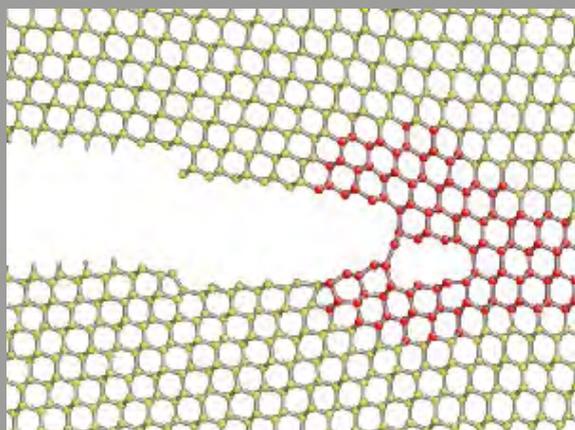
Above, top right: Prototype neutral atom microscope. The inset shows a calibration sample.

FUTURE DEVELOPMENTS

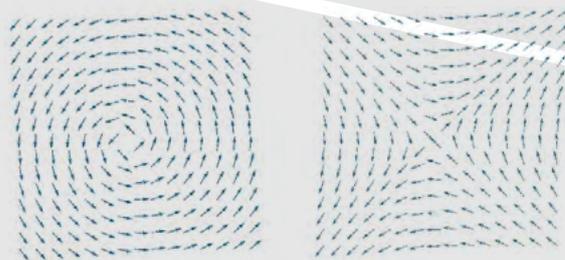
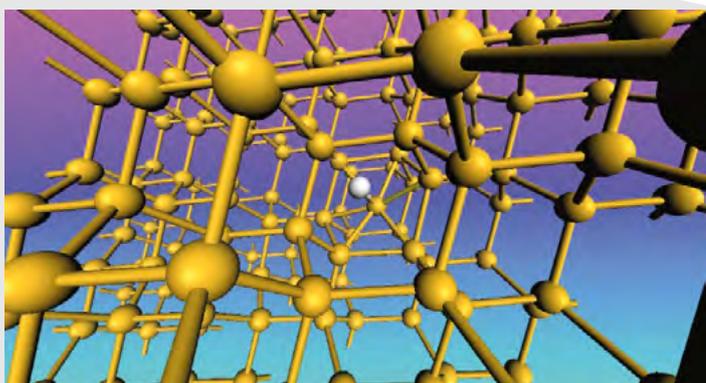
1. A major goal in the development of **antiferromagnetic materials** is to break the limits on miniaturisation set by dipolar fields in ferromagnetic nanostructures.
2. Advantages of **spin-based technology** are the low energies involved, leading to low-energy logic and energy harvesting.
3. **Spin-light interactions and ultrafast spintronics** can be based on THz radiation.
4. There already exists in Cambridge expertise in the interaction between **spins and artificially induced strains** for which there is great development potential.
5. In spintronics and quantum technologies, **spin-based qubits** are among the most robust implementations of quantum information. This interface between the two fields will be explored, building on recent work on coupling magnons to microwave photons in cavities.
6. There is the potential for an international network in **nanoscience with neutral atoms**.

Pulling it all together - the Role of Theoretical Physics

Theoretical Physics has played an essential and distinguished role in the success of the Laboratory's programme. Theoretical activity supporting the work in astrophysics, cosmology and high energy physics is described in the relevant research themes above. Originally under Bragg and Mott, theory played a major role in supporting the many initiatives in condensed matter physics led by pioneers such as Hartree, Ziman, Heine, Anderson, Josephson and many others. Their successors tackle a huge range of frontier research programmes in condensed matter physics. These include correlated quantum systems both in the solid state and in atomic gases, computational electronic structure, liquid crystals, complex networks and the statistical physics of emergent behaviour in cell biological systems. The principal themes of current research illustrate the cross-disciplinary nature of much of this research.



1. The **application of computational methods** to study solids and liquids using first-principles molecular dynamics based on density functional theory (DFT) is a major theoretical and computational challenge. These studies include quantum non-equilibrium processes related to radiation damage in condensed matter using real-time time-dependent DFT.
2. **Thermodynamics and equilibration properties** are studied for frustrated magnetic systems, classical and quantum spin liquids, slow dynamics in non-disordered systems and out of equilibrium properties in systems with fractionalized excitations.
3. **Topological states of matter** in quantum many-particle systems, encompassing both solid-state systems and ultra-cold atomic gases, is a major developing theme.
4. In **mesoscopic and ultra-cold physics**, there is an emphasis on disordered, low dimensional and non-equilibrium systems.
5. **Quantum Monte Carlo calculations and DFT methods** are used for calculating vibrational properties. DFT methods are employed in predicting crystal structures, including the high-pressure phase diagram of hydrogen and stabilization by anharmonic nuclear motion.
6. **First principles total energy calculations** using CASTEP has been a long-term success story and now has expanded to include the linear scaling code ONETEP, Gaussian Approximation Potentials and the Learn-on-the-Fly hybrid QM/MM methodology.
7. **Coherence phenomena** is a recurring theme in quantum condensed matter, with applications to mesoscopic and ultra-cold atom physics. Statistical approaches have been successfully applied to cell biological systems.
8. The development and application of methods to explore the **genome, epigenome and transcriptome** of single cells is being undertaken to understand normal development and disease processes in human and model organisms.
9. The **physics of soft matter**, one of the traditional strong theoretical areas pioneered by Sam Edwards, continues with an emphasis on the novel mechanics of nematic solids.



SYNERGIES

1. Major collaborations take place with experimental activities in the Laboratory, particularly with the Fundamentals of Quantum Matter, Statistical and Soft matter, and Biological and Biomedical research themes. Many collaborations are fostered through programmes involving the Maxwell Centre and the Winton Programme for the Physics of Sustainability.
2. Active collaborations take place in Cambridge within the Physical Sciences with Applied Mathematics and Theoretical Physics, Chemistry, Engineering, Earth Sciences and Materials Science, including the Centre for Doctoral Training in *Computational Methods for Material Science*.
3. Strong links have been established with the School of Biological Sciences, particularly with the Gurdon and Stem Cell Institutes, the School of Clinical Medicine and the Wellcome Trust Sanger Centre.
4. A broad network of UK and international collaborators has been created. Many international links are a result of the three major computational electronic structure codes CASTEP, ONETEP and CASINO, all of which have enjoyed major commercial success, and from SIESTA, a widely used open-source linear-scaling electronic structure code.
5. There are many Industrial collaborators, including Samsung, Rolls Royce, Granta, BP, Shell and BT.

FUTURE DEVELOPMENTS

1. The **major themes arising from the current strengths in theory** are in correlated quantum systems and topological quantum computation, many-body solid-state systems, biological theory and computational molecular biology.
2. There are important **emerging fields** which will require personnel in new areas of theoretical expertise. These include:
 - a. **New post in mathematical physics**, particularly in conformal field theory, integrable models and the AdS-CFT correspondence.
 - b. **New post in non-equilibrium statistical physics and active soft matter**.
 - c. Senior post in **information theory**, building on the inheritance of the late David MacKay.
 - d. New position exploiting the **manipulation and processing of 'big data'** within the broader context of condensed matter physics.

Opposite, bottom left: The red bonds involved a full quantum mechanical simulation of crack propagation in the crystal lattice.

Above, top left: A hydrogen/silicon defect in bulk silicon. The theoretical computations show that hydrogen breaks silicon bonds and may make it easier to charge silicon anodes.

Above, top right: A vortex and an anti-vortex in a 2-dimensional material. The angle (θ) of the local order, for example, the spin of a ferromagnet or the phase of a superfluid/superconductor, changes by either plus or minus 360° around a closed loop

Endowment of Professorships

One of the most effective ways of enhancing the overall prestige of the Laboratory and its research and teaching programmes is through the endowment of distinguished chairs. Although some of these were established long ago, the initial endowment has long ceased to cover even a small fraction of the salary costs of the most distinguished physicists we seek to attract. The endowment of Professorships releases resources that can be used to support the research and teaching programme of the Laboratory in very substantial ways.

Opportunities for Philanthropic gifts

We have identified a number of chairs for which endowment funds are sought. Established chairs include:

1. Jacksonian Professorship of Natural Philosophy, currently vacant;
2. 1966 Professorship of Theoretical Physics.
3. Professorship of Nanophotonics, currently held by Jeremy Baumberg;
4. Professorship of Thin-Film Magnetism, currently held by Russell Cowburn.

In addition, benefactors may wish to support distinguished professorships in other branches of physics and we strongly welcome such proposals.



Above: left to right: John Cockcroft, Nobel Prize winner in Physics 1951, Jacksonian Professor of Natural Philosophy. Phil Anderson, Nobel Prize winner in Physics 1977, first holder of the 1966 Professorship of Theoretical Physics, Jeremy Baumberg, appointed to the Professorship of Nanophotonics in 2007. Russell Cowburn, appointed to the Professorship of Experimental Physics in 2015.

The endowment of new Professorships always leads to major enhancements of the research and teaching activity. These endowments continue to be major and key components of the University's Development Campaign.

Teaching Initiatives

Physics is the largest Natural Sciences subject in the University, the number of students choosing the course having grown by about 30% over the last 8 years. We have never had such large numbers of students to teach and train. This large increase in numbers has not been accompanied by an increase in staff numbers.

The Department has no dedicated teaching staff such as Teaching Fellows and so the University Teaching Officers (UTOs) remain fully responsible for the delivery of the course and examinations. All UTOs are expected to contribute in teaching and research and make general contributions to the running of the Department. This traditional model is under great stress. Each of the four key work streams – research, education, administration, and College activities – are increasing their demands on academic staff.

The student-staff ratio is at a historically high value, caused by the large and steady growth in student numbers, the move to a four-year degree, the addition of the MAST degree, and the static UTO headcount. This unfavourable student-staff ratio has also increased recently due to the increasing opportunities and incentives for faculty to buy themselves out of teaching, and so focus entirely on research.

The new Teaching Excellence Framework (TEF) has begun, and will be developed in detail over the coming years. This greater emphasis on teaching evaluation via the TEF is in many ways welcome, and will balance the research evaluation through the Research Excellence Framework (REF).

Opportunities for Philanthropic gifts

There are many ways in which philanthropic gifts can provide support to the teaching programme. Examples include:

1. Endowment of Lectureships in Experimental and Theoretical Physics.
2. Support for young fixed term (three-year) lecturers.
3. Support of the programme of innovative physics experiments in practical classes.
4. Endowment of prizes for outstanding physics students through all years of the course.
5. Research support for young lecturers to carry out blue-sky research programmes which are at the very limit of present capability.



Top: A first year class in practical physics.

Bottom: A physics experimental project.

Graduate Students and Research Fellows

The Cavendish Laboratory Graduate Student Support Fund

Among the most important roles of the Cavendish Laboratory is the training of graduate students. At any one time there are about 500 students carrying out world-leading research in the Laboratory. They will become the future leaders of research in the UK and abroad in the years to come. The Laboratory has the capacity and desire to increase the size of the graduate student population in response to the exciting prospects offered by the research programme, and the national need for expert trained manpower of the highest intellectual and experimental attainment. Funding from external sources, such as government, is variable and often limited. We need to be able to offer our own funds to the very best students from the UK and elsewhere, giving them, and us, the freedom to develop new research areas.

We are more and more reliant upon these benefactions to ensure that we continue to attract and support the very best graduate students from the UK and abroad. The Fund may also be used to provide other types of support including training, equipment, travel expenses, and conferences at the discretion of the Managers of the Fund.

Pump-Priming the Next Generation of Physics Research

Many of the great discoveries in physics have come from speculative experiments, often running counter to the conventional majority view. The ability to encourage research physicists at all stages in their careers to attempt bold and innovative research is at the heart of some of physics greatest triumphs. For example, Lawrence Bragg discovered Bragg's Law of X-ray Diffraction in his first year as a graduate student and Brian Josephson discovered the Josephson effect in the second year of his doctoral studies.

A **Physics Research Support Fund** has been set up, bringing together existing funds within the Department and providing a simple means for benefactors to contribute to the research work of the Department at a wide range of levels. Often, small investments can have a quite disproportionate benefit in testing out ideas that cannot attract funding from traditional funding sources. The guidelines for the operation of the Fund are as follows:

- a. A Board of Managers, chaired by the Head of the Cavendish Laboratory and involving senior members of the Department, is responsible for the proper management of the Fund.
- b. The capital and income of the Fund is used to provide unrestricted grants to support the research in the Cavendish Laboratory. This might be in the form of fellowships, the provision of equipment or any other means of supporting innovative research within the Laboratory.



- c. There is no restriction upon the areas of research that can be supported by the Fund. The emphasis is on innovation and interdisciplinary areas where new ideas can be fostered and exploited.

Donations of all sizes to support these areas can make a huge difference. The Department would be pleased to discuss naming opportunities in recognition of a major gift, such as the endowment of a graduate studentship in perpetuity.

Top right. The Workshop Training Course proved very popular with the graduate students. Ugo Siciliani de Cumis and Egle Tylaite, the 78th and 79th students to complete the course, are shown with Nigel Palfrey with the devices they constructed from scratch. **Lower right.** Thanks to a philanthropic gift, an Inventors' Teaching Room was created. It contains state of the art Computer-Aided Design facilities and electronics training equipment to give graduate students experience in using these techniques under the guidance of Gavin Ross.

Outreach and Young People



4. The **Outreach Programme** is organised by our full-time schools' liaison officers, who run a very wide variety of programmes for schools and young people, supported by volunteers among the staff, graduate students and undergraduates. These endeavours include the Annual **Physics at Work Days**, which attract about 2,400 students each year and the **Cavendish Open Day during Science Week** and **Teacher Training activities**. The scope of these key activities is limited by the staff effort available to support them.
5. **Cambridge Colleges Physics Experience** provides opportunities for teachers and students from years 7 to 12 to experience a typical day in the life of a Cambridge undergraduate keen to pursue the study of physics. These days enrich the experiences of the student and their teachers and encourage young people from disadvantaged backgrounds to consider seriously applying to Cambridge.

The Physicists of Yesterday, Today and Tomorrow

1. The unique history and tradition of Cavendish physics is an inspiration for future generations of physicists and their teachers. The full potential of the historical collections and their role in education will be greatly enhanced by a fully-supported Cavendish Physics Centre, which would bring together many different aspects of the interface between the Cavendish and the external world.
2. The **Cambridge Physics Centre** is the vehicle for bringing together the various aspects of the programme to reach out to young people, their teachers and their families. Our ability to reach larger audiences is limited by the resources needed to redevelop and expand the exhibition area and the manpower to sustain the outreach and teacher training activity. The New Cavendish Laboratory has been designed so that outreach is a natural and welcoming activity for all types of visitors.
3. **The Cavendish Museum.** There is great scope for increasing the wealth of material on display for educational purposes. Much of the historic material remains in storage. An immediate programme would involve the refurbishment and expansion of the museum area, including many more interactive displays. In addition, there are opportunities to provide support for the display of the historical material in the New Laboratory.

Many possibilities for philanthropic support of this programme include funding a full-time **Director of the Cavendish Physics Centre** with the focus firmly on schools, teachers and young people and the support of **further outreach personnel** working under the supervision of the Director of the Physics Centre.



Top left: A Physics at Work demonstration of musical flames provided by the physicists from AWE.

Bottom right: The Cavendish Collection of Historic Scientific instruments.



School Physics with the Mathematics put back in

One of the great successes of our outreach programme to schools has been the pioneering **Senior Physics Challenge**. This summer course gives talented young people the opportunity to understand how physics works as a theoretical discipline with the creative use of mathematics. This programme is intended to address the problem of the decline of physics student numbers in the UK.

The two main aims of this programme are as follows:

- Many of the ablest school and college students, with aptitude in maths and a passion for physics, are not opting to study physics at university. The students' misconception about physics arises from the removal of much mathematically-based problem solving from the school curriculum. The activities and material they encounter in **the Senior Physics Challenge** are specifically designed to dispel many of these myths about physics.
- Universities seek fluency and ability in physical and mathematical analysis that are not given prominence in the current school physics syllabus. Some students and their schools are increasingly surprised and disadvantaged by the discrepancy between their expectations of higher

physics and its reality. The aim of the **Isaac Physics project**, sponsored by government, is to demystify, make more accessible and widen participation in physics to a wider range of students nationally and internationally. These endeavours facilitate the transition from A-level to university physics in the UK. It combines online study tools with face-to-face events at partner schools and institutions across the UK. By January 2017, 2,680 teachers from the UK and abroad had signed up as users and the number of students actively using Isaac Physics as a learning tool had reached 43,158. The total number of persons using the site is estimated at over 2.5 million.

The course is currently being supported by government with a major grant which will terminate in 2018. Beyond 2018, we have plans to continue to innovate in a digitally-enhanced learning environment which, given our experience, could be easily adopted by other disciplines in the physical and engineering sciences. This would require the support a dedicated organiser, ideally a bright young physicist, who would be employed as a Teaching Fellow.



Top left: Bright school pupils taking up the Senior Physics Challenge in the Maxwell lecture theatre in the old Cavendish Laboratory.

Bottom right: The on-line Isaac Physics project is designed to help school pupils develop their physics skills before they come up to University.

General Equipment Fund

One of the most helpful contributions to the research programme is through the provision of funds for general equipment. State of the art equipment is essential if the Laboratory is to maintain its position at the forefront of experimental physics. The problem is exacerbated by the fact that the Research Councils often only provide partial support for the purchase of equipment. For large equipment purchases, collaborations with other Departments are often essential, but during the early phases of many of the most innovative programmes, which would not have a chance of being funded by the research councils, there is a need for the investment of modest funds to enable the prototyping to be carried out. This often involves the expenditure of several tens of thousands of pounds.

Another example where contributions can make a real difference is through the purchase of components for projects constructed in-house, such as the helium-3 spin echo spectrometer. While many of the components could be built in the Laboratory, it is often preferable to purchase from specialist manufacturers.



Above: Leica VB6 UHR electron beam lithography machine for nanoscale patterning of semiconductor structures.

Below: The mechanical workshops with state-of-the-art CNC machines.



Industry and Commerce

A top priority of our strategic plan for Physics is the **practical application of physics research and teaching for the benefit of society.**

This means many things, but of central importance are our interactions and collaborations with the industrial sector. As significant as any of these is the large percentage of our graduates who find employment in the industrial, commercial and public sectors. But of more immediate importance is collaborative research with industry in fostering the transfer of discoveries in physics into the new technologies and techniques needed by industry. The Laboratory has a long list of more than 100 industrial collaborators, ranging from consultancies and research grants to full-scale embedded laboratories. Particularly notable are the long-standing and fruitful partnerships with Hitachi through the Hitachi Cambridge Laboratory contiguous with the Microelectronics Group, Toshiba's ongoing support of major projects in the Semiconductor Physics Group and AWE's long-term commitment in the areas of materials physics.

Equally important are the spin-off companies which have been created by members of the Laboratory who have been keen to exploit the fruits of their researches. These include companies such as Cambridge Display Technologies, Plastic Logic, Teraview and Accelrys.

The Maxwell Centre, opened in April 2016 is home to a programme of academia-industry engagement across Physical Sciences and Technology in Cambridge. It hosts researchers from Physics, other departments and industry, as well as several interdisciplinary activities, including Big Data and Energy@Cambridge Strategic Research Initiatives, the NanoForum Strategic Research Network, the Winton Programme for the Physics of Sustainability and EPSRC Centres for Doctoral Training (CDTs) in Nanoscience and Computational Methods for Materials Science. The activities are closely linked to industry with partners including aerospace (Boeing, BAE Systems), automotive (Jaguar Land Rover), mining (ORICA), defence (AWE, QinetiQ, Singapore Defence Laboratories) and oil & gas (BP, Schlumberger) sectors, as well as grants from EPSRC.

The Maxwell Centre is set up for open innovation through research, with a distinct environment for collaborative work, and a very mixed community, where strategy and serendipity thrive. It is also a hub for shared-access experimental facilities, such as the Cambridge spoke of the Henry Royce Institute for Advanced Materials, Nano CDT laboratories and the EPSRC/Winton Advanced Materials Characterisation Suite. The set-up of these experimental facilities optimises access to capital equipment within the University and beyond, including users from industry.



Above: The Maxwell Centre for collaboration between industry and the physical sciences, managed by the Cavendish Laboratory.

Industrial engagement days are organised by the Laboratory's Knowledge Transfer Facilitators. The primary purpose of these is to give Cavendish post-doctoral researchers and PhD students experience of considering industry-related research problems through structured discussions over a day. These have been very successful in developing new industrial-related projects in basic physics.

But this is only the beginning. In our vision of the future development of the Laboratory, there will be strong industrial collaborations involving all the Groups in the Laboratory and laboratory space will be created within each group for our industrial collaborators. The approach fostered by the Maxwell Centre is readily adapted to all the activities which will be pursued in the new Laboratory.

Engagement with industry on all scales is of the greatest importance to the Department and the strategy of the Department is to at least double this engagement when we move into the new Laboratory. With our enhanced national role, we are in a strong position to expand collaboration with industry to our academic partners and the broader University research community. We envisage this engagement to take place on all scales from small start-up companies, through SMEs to multi-national companies. **Do take this opportunity to talk with us well before we occupy the new Cavendish Laboratory.**

Future Buildings

The main thrust of the Development Portfolio described above is to ensure that we make a seamless transition to the new programmes of the research to be undertaken in the new building. At the same time, we recognise that the programme will expand and already we need to think about the necessary future stages to enable this to take place in a timely manner.

The RIBA Stage 3 Design of the new Cavendish Laboratory covers not only the building as it is intended to look when it commences operations in 2022, but also describes in detail two phases of subsequent expansion. Plans for the expansion will be submitted in the same application for Planning Permission as that for the main laboratory. This should then create the opportunity to add about a further 10% of usable space, without the need to repeat the planning process. These extensions include an extra floor of offices on top of one wing of the main building, and an additional block at the north-east corner of the plot, at the entrance to the West Cambridge site from Madingley Road. These extensions have been chosen to

ensure that their construction can take place with the minimum impact on the operation of the laboratory. The prominence of the north-east corner is such that great care is being taken to ensure that the design attains an exceptional architectural standard both before and after this addition is completed.

Another important development will be a new building at the Lord's Bridge Observatory for the provision of radio test facilities. The Astrophysics Group has built up world-leading capabilities in the design of antennae and antennae systems, which are in very considerable demand for pure science and for many applications outside astronomy. This activity is centred on the design of the antennae for the Square Kilometre Array project which is placing new demands upon the design and performance of radio antenna systems. There is an urgent need to construct antenna systems test facilities to maintain the momentum behind this programme, which involves many of the major radio observatories throughout the world.



Above: A visualisation of the low frequency antenna array to be constructed in Australia, based on development work carried out in the Astrophysics Group. The array will consist of over 100,000 such antennae with a collecting area of 1 square kilometre.

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 described in this edition of CavMag and is also available 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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