UNIVERSITY OF
BIRMINGHAM

Research

IN THE COLLEGE OF ENGINEERING AND PHYSICAL SCIENCES

Design, Discover, Deliver

www.birmingham.ac.uk/eps

Introduction

Our ability to be at the forefront of research is built on and shaped by the heritage of the College with its long-standing and pioneering achievements across the spectrum of basic and applied science and engineering since 1900. A characteristic of research at Birmingham are the synergies between theoretical and experimental endeavours, coupled with large-scale experimental facilities. Our facilities span the main Birmingham campus and at Ansty in the West Midlands and major collaborative activities in Switzerland (CERN), and China (Guangzhou, Hefei). This provides a diverse and unique environment for our scholars and their research groups.

From atoms to astronomy, computers to cars and railways to robust extreme environment materials, our wish is to transform our understanding of complex systems to build intellectual talent – expressed in high calibre people – and to improve global well-being and our economy.

Across the College the breadth of expertise in discovery science and in bringing innovation to societal use through engineering is extensive. We actively encourage an entrepreneurial spirit in our research community and business networks to ensure knowledge exchange. Our research has impacted society in many ways. Our portfolio of capabilities and selected achievements may be summarised in three key overarching themes:

- **Advanced manufacturing** – driving the industry forward by staying head of the global competition through our innovation
- **Science frontiers** – fundamental breakthroughs in our understanding of the way Nature works
- **Resilience, energy and sustainability** – tackling the challenges of future generations now

Making important discoveries in fundamental science is both exciting and revolutionises the way we think about the world around us, but transferring these discoveries to applications has seen some of the major transformations in technology. This requires connectivity between fundamental science, engineering and ultimately business and industry. That is what we do at the College of Engineering and Physical Sciences – and we are striving hard to develop further.

Professor Richard A Williams
Pro-Vice-Chancellor and Head of College

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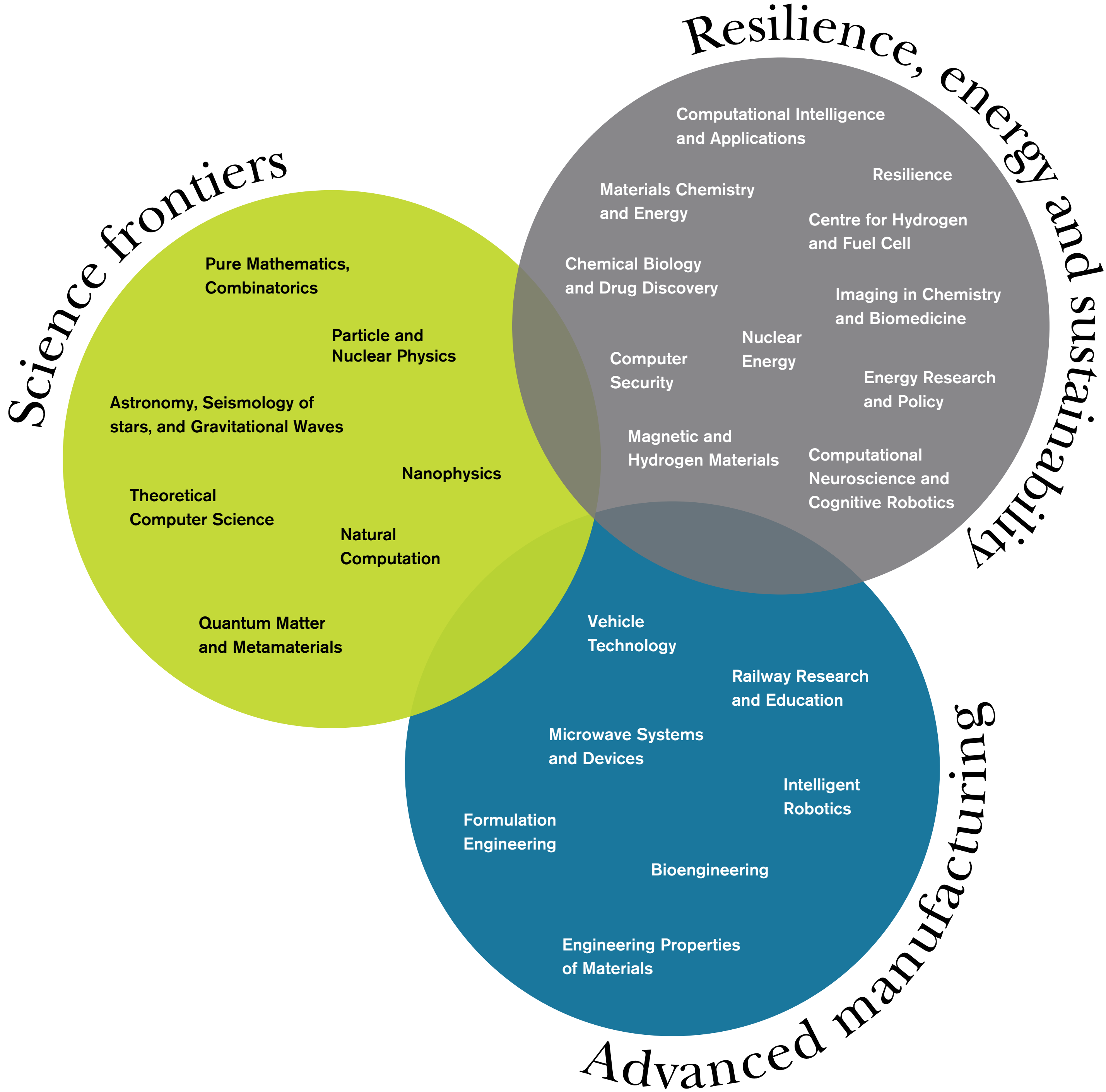


Advanced manufacturing

Advanced engineering and manufacturing are pivotal to the UK's business success, at home and abroad. Birmingham has long aligned its research programmes with industry and national priorities – and we now lead the way in key areas.

We are developing engines of the future and designing tomorrow's railways – from materials and modelling to power and risk analysis. The drivers being efficiency, reduced environmental impact and safety. We are driving advances in the aerospace sector, including novel materials and fabrication methods for aero-engines; our expertise underpins some of the most advanced engine designs.

In design and manufacturing of electronic devices, we are working on radio frequency and microwave engineering – to help meet the demand for new, internet-based services on small and mobile devices and systems for advanced automotive radar.

A major frontier is the development of artificial biological materials, such as bone, for use in surgical substitution. The challenge is to develop materials that are not only structurally similar but behave the same as the material they replace. This ground-breaking research is only possible because we have the technology and the know-how coupled with our development of cutting-edge techniques for enhanced imaging of biological systems.

We have extensive research in formulation of soft structured products such as food, fuels and products such as washing detergents.

In all of these, we work alongside global industry partners such as Jaguar Land Rover, Procter and Gamble, Rolls Royce and Unilever.

Advanced Materials Engineering
Formulation Engineering
Engines for the future
Automotive radar

www.birmingham.ac.uk/advanced-manufacturing

Advanced Materials Engineering

We are leading UK research in developing advanced resource-efficient processing techniques for a variety of metals – such as nickel, titanium and aluminium – to make a range of state-of-the-art components using revolutionary technology.

3D Printing of Advanced Engineering Components

More properly known as 'additive manufacturing' or 'selective laser melting', we are able to 'print' complex items, such as an engine component, in their finished state rather than machining them from the bulk. Using lasers to melt a metal powder, we print the component by adding layer upon layer of the powder. We are at the heart of the 'third industrial revolution' – using 3D printing techniques to make components out of metal. We are the only university in the UK to use a variety of metals in this way, especially the laser and powder based techniques.

Net Shape Manufacturing

This technology, used to manufacture large components from metal powder to final shape in just one step, is known as 'net shape'. It works by filling a mould, designed through sophisticated computer modelling, with powder and then applying temperature and pressure so that the powder holds itself in the shape required – an engine casing, for example. As with other novel engineering technologies, net shape manufacturing is much more efficient than traditional methods, with buy-to-fly ratio (the weight ratio between the raw material used for a component and the weight of the component itself) slightly over 1, compared to about 10 for material removal processes: 60 kg of powder will make 56 kg of engine casing. This method also requires minimal finishing. In traditional manufacturing, machining work can account for *two-thirds* of the price of a component.

Direct Laser Deposition

Traditionally, if, say, an expensive turbine engine blade breaks or becomes worn, it is discarded and replaced. But we are exploring the use of metal powders to 'fill' the worn or broken bits. Again, the benefits include cost-reduction and increasing the product life.

These new approaches to manufacturing are transformational:

- The lead-time, from design to production, is much shorter than using casting and forging. It can take just two days to make a geometrically-complex component.
- They are resource-efficient. Nickel, for example, is very expensive material. Manufacturing by machining, removing metal, results in a lot of waste.
- The buy-to-fly ratio is vastly reduced. For example, with traditional methods, 10 kg may be required to make a 2 kg component, whereas with 3D-printing, just a little over 2 kg will be required to make the same component.
- They create products to a higher specification and dimensional accuracy.

Additive manufacturing is one of several novel techniques we employ to take engineering into a new era – where industry is able to design for functionality rather than manufacturability – bringing new prosperity to the UK. Moreover, this approach minimises manufacturing's carbon footprint through the three Rs – Reusing, Recycling and Remanufacturing (repairing) of existing products. This is an example of 'high-value manufacturing' (HVM), where Birmingham's advanced technical know-how is used to develop products and manufacturing processes that can bring sustainable growth and prosperity.

We are at the forefront of net-shape manufacturing technology – making large components from metal powder to final shape in one step. This is known as Net Shape HIPping (Hot Isostatic Pressing) and overcomes the waste in traditional manufacturing.

We are pioneering the use of the technique of direct laser deposition to repair worn components, such as engine blades, using metal powder, or to build large structure by free-form laser deposition.

We are founding partner of the Manufacturing Technology Centre (MTC). The MTC represents one of the largest public sector investments in manufacturing for many years and is housed in a 12,000 square metre purpose built facility at Ansty Park, Coventry for advanced manufacturing. It is a partnership between some of the UK's major global manufacturers and the universities of Birmingham, Nottingham and Loughborough. The MTC founder members include internationally renowned companies such as: Aero Engine Controls, Airbus and Rolls Royce. There are now more than 50 members representing a broad range of industrial sectors.

Formulation Engineering

Imagine a chocolate bar that is low in fat yet tastes just as luxurious as its full-fat counterpart. Thanks to world-leading research by our chemical engineers, you may not have to imagine for much longer. Our scientists have found the solution to making foods healthier but without compromising their taste and texture.

The Queen's Anniversary Prizes
For Higher and Further Education
2011

Working closely with the food industry, the aim is to help reduce food-related diseases like obesity and hypertension by encouraging the population to cut down on sugar, fat and salt. Until now, the big problem has been that low-fat and low-sugar varieties of convenience foods simply aren't as flavoursome and therefore not as appealing. What's more, many such products replace natural ingredients such as fat and salt with artificial alternatives, thus compromising their 'healthiness'.

What we do is to use process science to understand and manipulate food on the microscale to engineer products that deliver consumer expectation but with controlled energy and salt delivery so as to give a dramatic reduction in the amounts of fat, sugar and salt consumed in the diet. For example, we have found a way to substitute some or most of the fat globules in foodstuffs such as chocolate, mayonnaise and margarine with alternative, natural materials such as water.

So successful is our research that the food industry may be only two years away from bringing products that are as healthy as they are indulgent to market.

We are also revolutionising future health care and medical treatment. We are working to develop cell therapy treatments for regenerating diseased or damaged bones, cartilage, ligaments, skin and even eyes, and to improve the body's ability to heal. This might seem a million miles away from chocolate, but the principles are the same.

We are designing a material that is structured in a way that encapsulates cells and locates them in a position where they have a therapeutic effect. The release of the restructured cells is then done in a controlled way so as to enhance their benefit.

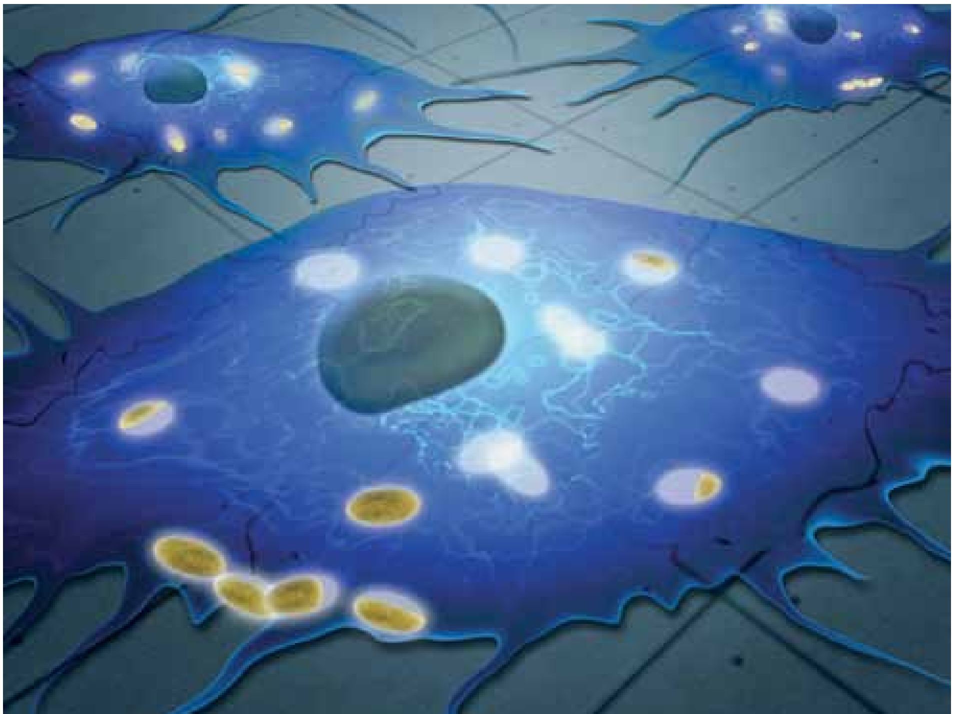
This research focuses on taking a population of cells from a person's own tissues, encapsulating them into a gel – which acts as a filler – and injecting it into that person's body. From there, the cells will excrete growth factors, which will encourage healing.

As our knowledge of biological systems improves, we are moving from the use of materials as crude compositional mimics, to designing ones that can interact with specific biological processes to enhance tissue formation.

Because of our strengths in the design and characterisation of microstructured products, and in heat and mass transfer, fluid flow, particle technology and materials engineering across chemical, biological and physical systems, we collaborate with world-class industry, as well as with leading-edge engineering and science departments nationally and internationally.

The School of Chemical Engineering was awarded the Queen's Anniversary Prize for Higher Education in recognition of its pioneering research in micro-structured materials and outstanding track record in collaborative research and training with UK and multinational companies involved in process engineering.

We are the largest group of its type in any UK academic engineering department – we have 30 PhD and engineering doctoral students working on these projects.



Engines for the future

The engines of today are both powerful and efficient, but the engines of tomorrow need not only to be powerful and efficient but significantly greener. Our mechanical engineers are working with some of the biggest names in industry to develop future fuels (including biofuels) and new combustion system/after treatment to reduce the environmental impact of transport. We work closely with UK industry in engine design and advanced engine technologies, helping to design the engines and fuels of the future.

Our exceptional engine research and development labs are second-to-none: Our Future Engines and Fuels Laboratory houses ten engine test bed facilities for engines, fuels and catalysts and it is here that we carry out extensive collaborative work with the likes of Jaguar Land Rover, Ford, Johnson Matthey and Shell.

The main challenge in engine development is to enhance fuel efficiency and the reduction of emissions such as nitrogen oxides and carbon monoxide. Changing the way fuel is injected into the cylinder can improve both combustion and performance. Our facilities for new combustion mode (eg, homogeneous charge compression ignition) include a glass cylinder in which it is possible to perform world-leading measurements of fuel injection and combustion.

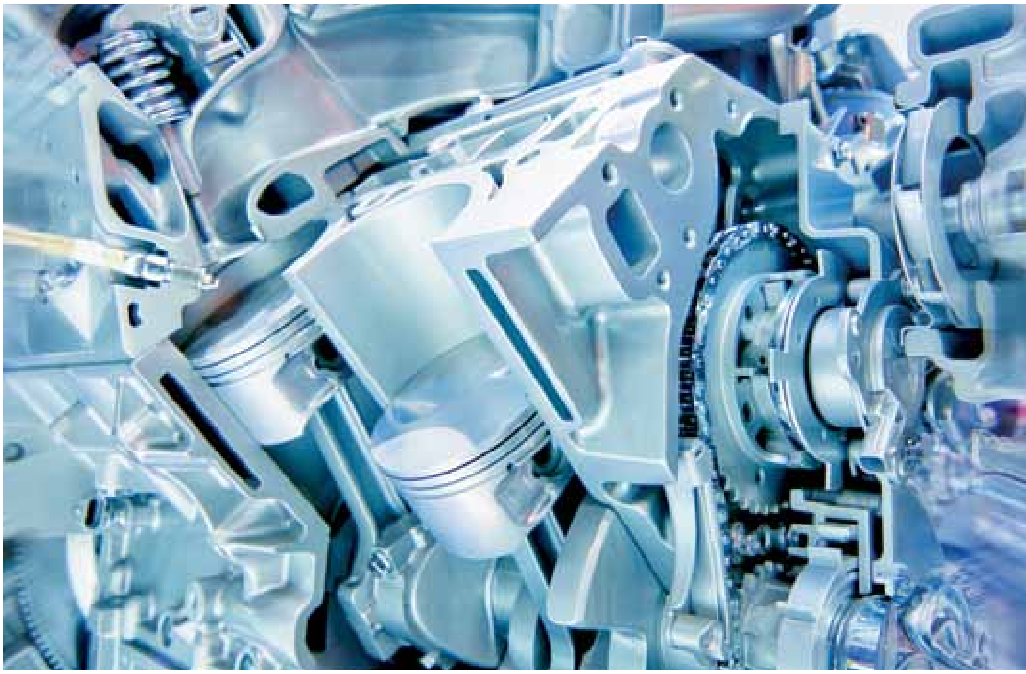
Biodiesel can be manufactured from, for example, vegetable oil. This is used in blended fuels, the global consumption of which is about 30 billion gallons per year. Our research has helped manufacturers to understand the possible proportion of biodiesel in order to both optimise performance and reduce carbon dioxide and other regulated emissions.

We are working with Jaguar Land Rover (JLR) to improve current and future generation engine technology, as well as on next generation gasoline direct injection combustion technology.

Using Birmingham research, JLR has been able to improve the flexibility of its engine technology to accept a wide range of environmentally-friendly fuels.

With the results of our research, Johnson Matthey has been able to optimise its environmental catalyst technology. This is helping to reduce regulated and unregulated pollutant emissions, thus lessening the environmental impact.

Shell is one of the largest purchasers and distributors of biofuels in the world. Through Raízen, a joint venture between Shell and Brazilian firm Cosan to produce ethanol from Brazilian sugar cane, it produces more than two billion litres of biofuel annually. We have helped the company to design fuels that are compatible with current engine technologies.



Automotive radar

Making cars ever-more exciting to drive while at the same time improving road safety are two key components for maintaining pole position in automotive manufacturing. Cutting-edge radar research at Birmingham over two decades has powered the industry into the 21st century.

Our communications engineers have been involved in the research and development of ‘adaptive cruise control’ (ACC) radar and ‘blind spot monitoring’ (BSM) from the very beginning.

Both are now integral to the Jaguar Land Rover (JLR) range: ACC radar was introduced by Jaguar in 1999 and other car manufacturers have also started incorporating it into their vehicle design. Birmingham’s research in this sector continues to lead the way in the UK.

ACC enables a vehicle to automatically adjust its speed, by controlling the throttle and brakes, to maintain a safe distance from a target vehicle ahead and other objects nearby.

Our engineers have also worked on pedestrian and collision-avoidance systems, such as investigating the effects of rain and spray and radar interpretation of vehicles, pedestrians, animals, bicycles and road infrastructure.

We were integral to the EU Technical Committee setting the European radio frequency spectrum standard on automotive radar. We provided radar expertise to the committee, which included members from Birmingham, BMW, Daimler Benz, Fiat, Volvo, M/A Com, Siemens and GEC Plessy.

We have delivered training programmes in ‘understanding automotive radar: theory, practice and current development’ to Jaguar Land Rover

Our research has helped to improve vehicle efficiency, capability and road user safety. Optimum vehicle progress control offers environmental benefits by reducing energy wastage through inappropriate driving and also lessens damage to the terrain.

Science frontiers

Our research has delivered breakthrough discoveries which are challenging the understanding of the universe, its laws and fundamental characteristics. We have world-leading research programmes that reach from the smallest to the largest scales, from quarks to galaxies, through to challenges of pure mathematics and computing.

We are probing what happened an instant after the Big Bang, have helped discover the Higgs Boson, are leading the quest to find gravitational waves, and have led the way in developing experiments that can 'see' inside the sun and other stars. We are discovering new planets around distant stars, which are similar to Earth, in the habitable region known as the *Goldilocks Zone*.

We are developing new quantum materials – metamaterials – changing the way materials respond to light and microwaves and could lead to the fabrication of human scale invisibility cloaks. We are conducting research on human cognition and robotic systems, leading to a better understanding of both brain function and advanced robotics.

Astronomy
Particle Physics and Nuclear Physics
Combinatorics
Quantum Matter and Metamaterials

www.birmingham.ac.uk/science-frontiers

Astronomy

The possibility of finding other planets on which life might exist, is coming closer – thanks to research by astronomers at Birmingham. We listen to the 'music of the stars', elsewhere in our galaxy, around which new planets are being discovered. The characteristic pitch of the oscillations of the stars reveals their size and composition.

Our scientists are working with the Kepler Mission, a space observatory launched by NASA to find potentially habitable planets like our own, orbiting stars like our Sun, outside our solar system. Already it has produced dramatic results.

Our astronomers are studying the planets' 'suns', because the more information we can gather about the neighbouring star, the more we will know about the planet and the possibility of life elsewhere in the universe.

Our task is to characterise the host stars around which new planets are discovered, using a powerful, rapidly-growing field of astronomy called asteroseismology, which is the study of the stars by observation of their natural resonances which manifest as characteristic oscillations, similar to how resonating musical instruments are detected by our ears.

We are leading an international team of scientists, which is playing a leading role in this exciting international project.

Our work with the NASA Kepler Mission is enhancing our understanding of the life-cycles of stars, which will help us to better understand our own Sun. We can select for study stars of solar mass and composition that are younger and older than the Sun – allowing us to study the 'Sun in time' and open a window on the past and future of our star. This will enable us to better understand the potentially damaging effects on the Earth of solar storms and 'space weather'.

Our scientists played a major part in the detection of a rocky planet – smaller than our solar system's smallest planet, Mercury – orbiting a solar-type star 80 per cent of the size and mass of the Sun. The exact dimensions of the star, and the absolute size of the planet, were determined by asteroseismologists led by Birmingham.

We are an international collaboration of asteroseismologists that are studying Sun-like stars, using Kepler, and we are represented on the Kepler Exoplanet Council. We have published hundreds of research papers in scientific journals.

Particle Physics and Nuclear Physics

The discovery of the Higgs boson which gives mass to fundamental particles – was one of the biggest discoveries in physics in half a century. Our pioneering research helped to track it down. The identification of this tiny particle, predicted by Peter Higgs in 1964, has revolutionised the way we think about the fundamental mechanisms at work in the universe.

This endeavour is being spearheaded by CERN – the Geneva-based European Organization for Nuclear Research – and our elementary particle and nuclear physics groups are involved in as many experiments at the laboratory as any other group in the UK.

These – ATLAS, ALICE, LHCb and NA62 – are being conducted at the Large Hadron Collider (LHC), the world's biggest and highest-energy particle accelerator, which was built by CERN to enable physicists to test the predictions of different theories of particle and high-energy physics.

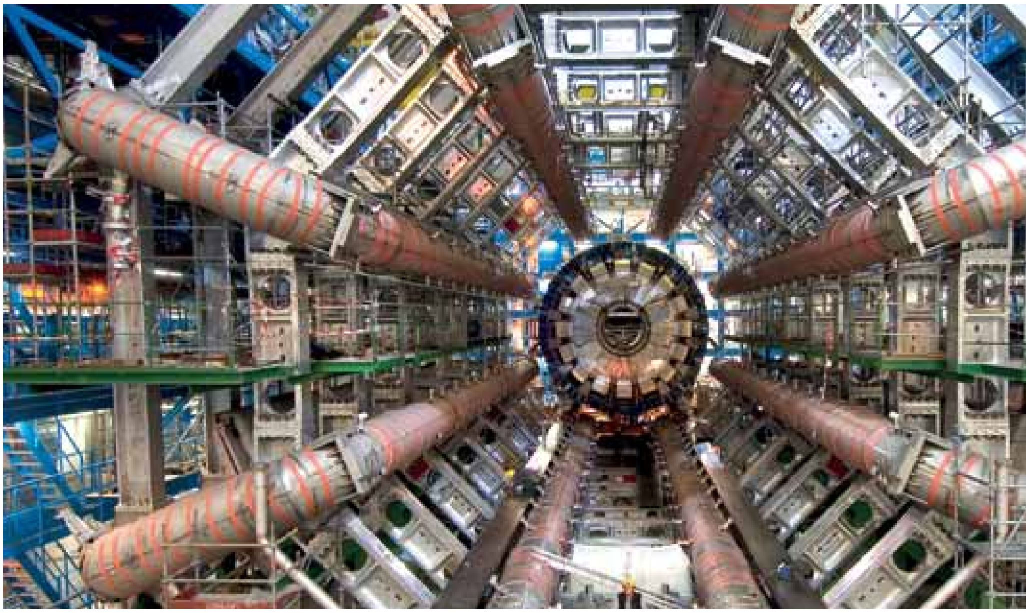
As part of the ATLAS experiment – a collaboration of nearly 3,000 scientists – our physicists performed some of the key analysis that resulted in the discovery of the Higgs boson in ultra-high energy proton-proton collisions at the LHC.

We are now busy testing our standard model theory against the Higgs' properties and looking for signs of even more exotic physics.

With the ALICE experiment, we are probing the nature of matter an instant after the Big Bang which resulted in the creation of the Universe. This will help us to understand how the Universe came to be the way we see it today.

Through precise measurements of the lifetimes of particles containing *beauty* quarks and antiquarks at the LHCb experiment we are trying to understand why there is more matter than antimatter in the Universe – after the Big Bang there should have been equal amounts of matter and antimatter, so where did all the antimatter go?

All these experiments require human endeavour at the cutting-edge – the extremes of energy, precision and technology. We are world leaders in the design and construction of state-of-the-art electronics that are needed to identify the most interesting collisions at the LHC within two-millionths of a second.



We have been involved in the discovery of the quark-gluon plasma, which will help us to understand how the universe came to be the way we see it today and also give us an insight into the structure of matter within the cores of neutron stars.

Our research programme is pushing the frontiers of instrumentation and radiation detection. The advances we've made have potential for producing sensors that function in high temperature environments, such as aircraft engines.

Combinatorics

The Travelling Salesman Problem (TSP) has baffled mathematicians for more than 50 years, yet two of our professors have ‘half-solved’ it; in the field of Extremal Combinatorics, that is no mean feat.

The question posed by the TSP is: ‘If you have a group of cities at various distances from each other, what is the shortest possible route a travelling salesman could take so he visited each city only once and returned to where he started?’

What makes the TSP such an intellectual challenge is that the number of solutions is so vast that there’s no efficient algorithm – it is well beyond the capacity of current computers to solve.

But as world leaders in our field – we have come closer than anyone has come before. An algorithm was devised to map a route that was in the top half of the list of all possible routes (ranked according to their length) – a vast improvement over any previous results.

Surprisingly, this breakthrough came via their solution of a famous conjecture on Hamilton Cycles in graphs – made by the mathematician PJ Kelly: the connection between the two is not obvious and was, therefore, unexpected.

In graph theory, the vertices or nodes represent cities and the edges between them represent possible routes the salesman could take.

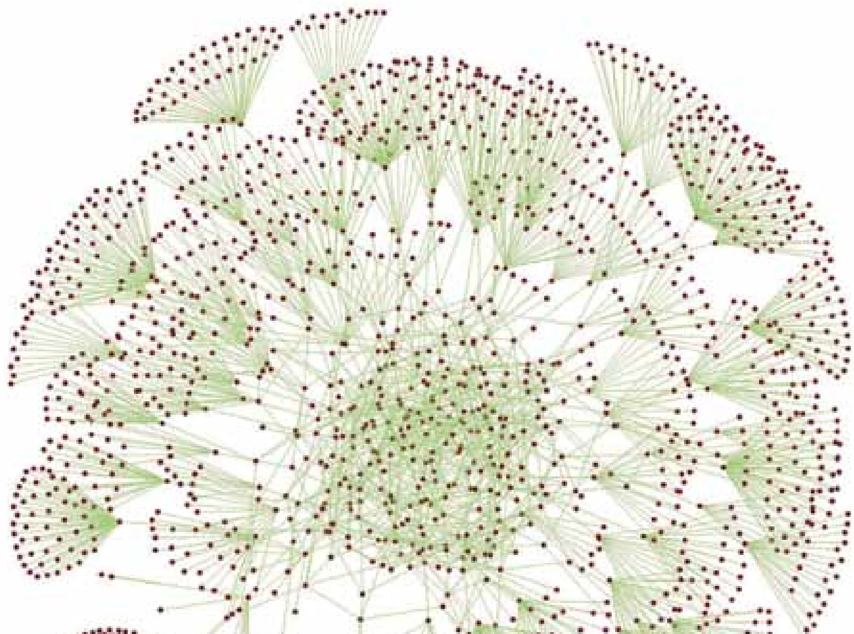
Our proof spans almost 90 pages (!) and has also led to the solution of other notoriously difficult-to-solve problems.

Although graphs are an abstract concept, they can be applied to many real-life situations, such as modelling social networks (the vertices of a graph representing people and the edges between them representing mutual acquaintances), as well as networks and structures in biology, communications, computer science and genetics. For example, applying graph theory to the internet enables you to see how resilient the network is to attack or component failure.

We hold two European Research Council Starting Grants. So far, only 16 such grants have been awarded to mathematicians in the UK, and only seven to combinatorialists in Europe.

We have also applied our methods to other classic mathematical problems: for example edge-colourings of graphs (which can be applied to real-life situations such as school timetables and other scheduling problems) and matching problems (which can be used to decide which teams of colleagues will work best together).

In Probabilistic Combinatorics, a major new research direction is to study random graph models that capture typical features of real-world networks such as the Internet – carried out at Birmingham. One current research focus is on random graphs on the hyperbolic plane (this involves unusual geometries such as those featuring in many of MC Escher’s pictures). Surprisingly, these graphs turn out to capture crucial features of such networks.



Quantum Matter and Metamaterials

Imagine the ability to make everyday objects invisible – even ourselves. It sounds like a science-fiction scenario, but our quantum physicists are working to develop an 'invisibility cloak' to do just that.

We have developed the first macroscopic example of a material capable of hiding from view a small object by bending light waves around it. These novel materials – known as metamaterials (materials engineered to have electromagnetic properties that may not be found in Nature) – diffuse light so that even the target's shadow is obscured.

To date, only very small objects have been rendered invisible – we have made a paper clip disappear – but we are among the world's leading quantum scientists working towards making objects as large as human beings appear invisible.

Using the same science, we are also developing ways to enable biologists to detect and therefore analyse viruses earlier, and to analogue certain astrophysics phenomena, such as black holes.

Manipulating matter so that it behaves unnaturally – but to our benefit – is also done through 'cold atom' science: cooling atomic matter to almost absolute zero – 0 Kelvin degrees or -273.15°C – to bring about a change in its behaviour. Close to absolute zero atomic matter behaves in an extraordinary way. Quantum matter can either be fermionic or bosonic, if it is the latter then at 0 kelvin the collection of atoms behave like a single *superatom*.

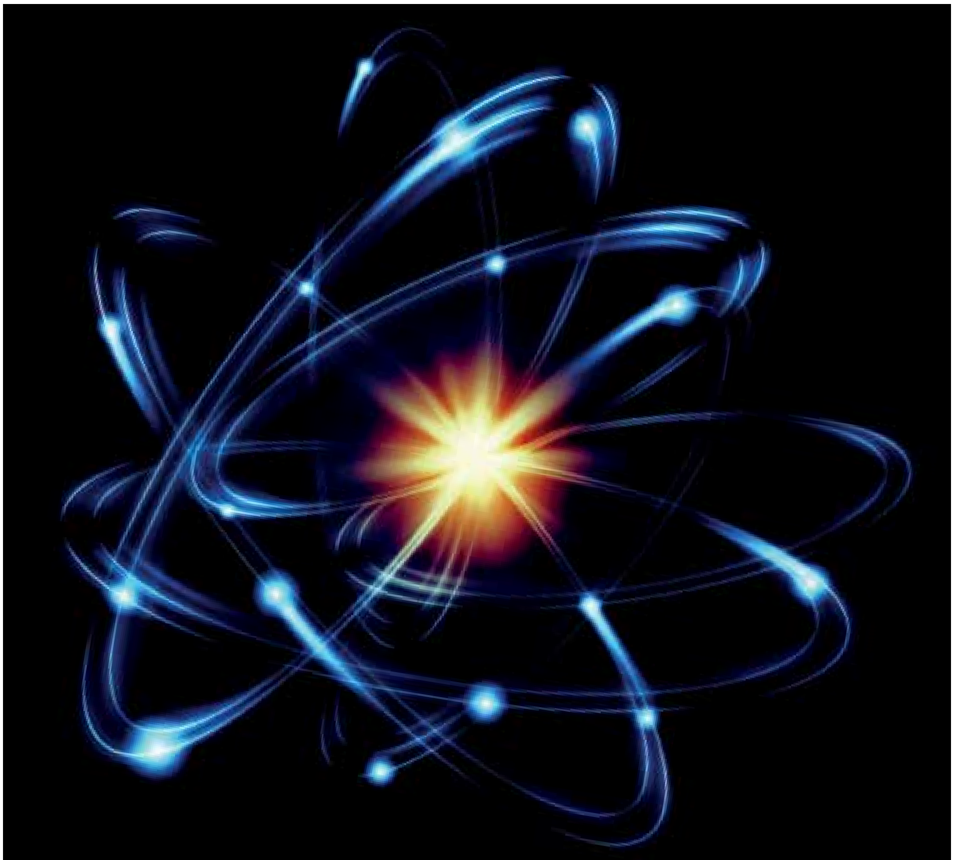
Using matter waves – made by exploiting the particle wave duality of an atom – which react to gravity, we are able to detect objects and other matter where even 3D sensing technology cannot. Although still in its developmental stage, we are working on gravity sensor technology to aid archaeologists and civil engineers.

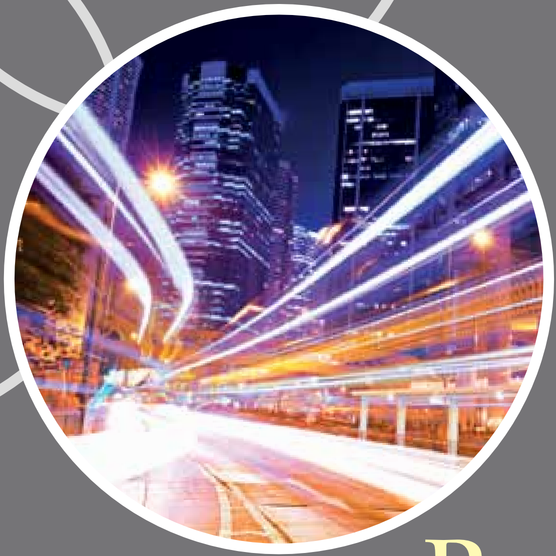
We have developed this research to be – almost literally – ground-breaking. Mapping the Underworld and Assessing the Underworld – both multi-million pound research projects – aim to find ways to locate pipes and cables beneath our streets without the need for excavation.

We have developed new types of materials with electromagnetic properties that have the potential to revolutionise the field, with huge translational possibilities.

We are EU leaders in developing a highly novel gravitometer that will be capable of detecting minute changes in gravity, enhancing our ability to detect anything from new oil reserves to archaeological treasure.

Quantum devices based around the cold atom science allows for precision measurements. We are developing novel compact atomic clocks that surpass current time standards by orders of magnitude and might boost the next generation, high-speed communication networks and satellite navigation.





Resilience, energy and sustainability

Our research is driving both the technology and thinking required to solve some of the challenges facing the UK as it seeks to develop sustainable solutions to the designing of future cites, energy and transportation. It is the ability to combine the practical with the radical which has placed Birmingham at the forefront of this endeavour.

The way we design the cities we inhabit shapes the way they function and the type of society they engender. Designing more 'resilient' cities, requires thinking in a seamless fashion about energy, water supply, transport, building design and construction – we are leading the way in both by developing the thinking and providing advice to local government.

Our researchers are meeting these considerable challenges in several ways. We are the UK's national centre for hydrogen research into the generation, storage and use of this energy source, as well as fuel cell-enabled vehicles. We are developing the UK's first national centre for Cryogenic Energy Storage and related thermal materials research.

We also design sustainable infrastructure and systems for cities and develop 'smart' technologies for the design and control of utilities for the urban environment.

Our work on artificial intelligence and robotic systems is helping design systems of the future which will enhance the potential in everything from medical surgery to manufacturing; we are helping improve the way robots see and understand their world and ours.

The way we use technology in the future will be different to today.

Chemistry for Health and Sustainability
Future Cities
Mapping the Underworld
Railways
Hydrogen and Fuel Cells
Energy
Robotics and Human Interface Technologies
Cyber Privacy

www.birmingham.ac.uk/resilience-energy-sustainability

Chemistry for Health and Sustainability

Our leading research in chemistry focuses on health, energy and sustainability, mapping squarely onto pressing national and global issues.

By working at the interface of several disciplines, as well as being strong in fundamental areas of theoretical and experimental Chemistry, research in the School of Chemistry is creating real societal impact. The Chemistry-Life Science and Chemistry-Medicine cross-overs exploit biointerfaces, bioimaging and biosensors, for example facilitating drug design. In collaboration with Chemical and Materials Engineering, Materials Chemistry is helping develop fuel cells, which can efficiently convert chemical energy from a fuel into electricity through chemical reactions. Research in these areas is underpinned by computational studies.

Chemical Biology and Drug Discovery

Our researchers are exploiting the power of catalysis and synthesis to generate new molecules and materials, which are being used to probe the function and behaviour of biological systems, source new drug molecules and generate drug delivery systems, such as nanoparticles whose application in drug delivery is set to spread rapidly. With a large, well-established and vibrant research base in the life sciences and medicine at Birmingham, the possibility for translating fundamental chemistry into therapeutic application is very real; diseases currently being targeted include various cancers, TB and irritable bowel syndrome, together with infection, resistance to antibiotics and vaccine development.

Imaging in Chemistry and Biomedicine

Our research is developing the chemical tools and materials required to image biological systems, and in so doing, provide new insights into how they function at hitherto unprecedented resolution. It draws together synthetic and biological chemists interested in molecular probe design and physical and computational chemists developing instrumental approaches to imaging. New fluorescent, Magnetic Resonance Imaging and molecular probes are being developed for imaging blood flow, labelling and tracking cells, and visualising and quantifying receptors to guide therapeutic treatment. This research is leading to new understanding in diverse areas ranging from sperm movement and modelling of force generation by flagella to adhesion of platelets and leukocytes to the walls of vessels, vital for understanding thrombosis and inflammation.

Materials Chemistry and Energy

Materials chemistry covers subjects from ceramics to nanomaterials, biomaterials and organic solids. Our research underpins a range of industrially important areas, with a major focus on new materials for energy technologies. Efficient energy storage and production is a grand challenge facing our society, and meeting this challenge requires new directions to achieve the step change in performance to make the necessary advances. Our research is targeting the next generation of materials for hydrogen storage, fuel cell, battery, solar cell, and nuclear industries. This research is underpinned by fundamental experimental and computer modelling studies into the role that the chemical structure plays in dictating the underlying properties of materials, leading to strategies for the rational design of new materials with improved properties.

The Analytical Facility in the School of Chemistry brings Mass Spectrometry, Nuclear Magnetic Resonance Spectroscopy, Chromatography, Elemental Analysis and X-Ray Diffraction/Fluorescence together under one section to provide the very highest quality of data analysis. With our excellent facilities and high level of expertise, we can offer our analytical services to other Schools across the University and external commercial organisations.

The Centre for Physical Sciences of Imaging in the Biomedical Sciences (PSIBS) was set up through a prestigious EPSRC award to facilitate the training of high-quality engineering and physical sciences graduate students in a multi-disciplinary environment at the Life Sciences Interface. The focus of PSIBS research is on the development of imaging techniques and the computational analysis of image data to enable and support future breakthroughs in biology and biomedicine.

Future Cities

Across the globe and throughout history, cities have been the centres of commerce, cultural evolution and innovation. People in cities have tended to be more productive, wealthier, better educated and also more resource intensive. Our researchers are helping think about how to design the cities of the future.

With populations rising, how do we plan, design and manage cities that can cope with increasing pressure on resources while meeting carbon and climate challenge needs? Will our investments in cities and infrastructure today still be resilient in a changing future? Can we design for long-term sustainability unaware of future technologies? How do we re-engineer cities to reduce the carbon footprint by 80% whilst retaining societal wellbeing?

Academics at the University of Birmingham are trying to tackle the needs of future generations today. These interdisciplinary challenges require collaborative solutions and consequently the University of Birmingham is providing leadership by bringing together a team of 35 specialists from the Universities of Southampton, Lancaster, UCL and Birmingham.

'Liveable Cities' is an ambitious national programme of research to develop a method of designing and engineering low carbon, resource secure, wellbeing maximised UK cities. The team are developing a unique City Analysis Framework that will measure how cities operate and perform in terms of their people, environment and governance, taking account of wellbeing and resource security. The aim is to develop realistic and radical engineering solutions for achieving the UK's ambitious carbon reduction targets which will be tested in three UK cities.

With engineering solutions comes the challenge of implementation. We are collaborating with the Universities of Newcastle and Leeds to establish the i-build centre. The centre will support the development of our understanding on what new business models are needed to develop our national systems of infrastructure networks (eg, energy, water, transport, waste). These systems support services such as healthcare, education, emergency response and thereby ensure our social, economic and environmental wellbeing.

Continued delivery of our civil infrastructure, particularly given current financial constraints, will require innovative and integrated thinking across engineering, economic and social sciences.

The i-BUILD centre will deliver these advances through development of a new generation of value analysis tools, interdependency models and multi-scale implementation plans. These methods will be tested on integrative case studies that are co-created with an extensive stakeholder group, to provide demonstrations of new methods that will enable a revolution in the business of infrastructure delivery in the UK.

Mapping the Underworld

To engineers, underground pipes represent buried treasure and beneath our feet lies a veritable trove – a vast network of pipes and cables on which we depend for our utility services. To install more, or find and repair existing ones, about four million holes are dug into the UK road network each year, resulting in traffic disruption, high costs and wasted man hours.

Part of our long-standing research into civil infrastructures is a ground-breaking research project, aimed at finding ways to allow this important work to be done without the need to dig holes and trenches. Together with several other leading UK universities, as well as the British Geological Survey, the multi-disciplinary team is developing the means to locate, map in 3D and record – using a single shared multi-sensor platform – the position of all buried pipes and cables without having to resort to excavation.

The cutting-edge work has combined a range of technologies – ground penetrating radar, acoustics and low-frequency active and passive electromagnetic field approaches – and intelligent data fusion with the aim of achieving a 100 per cent location success rate without disturbing the ground.

Our research in this area is evolving and paving the way for exploration into other project areas including an innovative 'body scanner for the streets'. This uses the same multi-sensor, non-invasive approach to assess the condition of the buried infrastructure, as well as the ground in which it is buried and the roads that overlie it.

A successful feasibility study for Mapping the Underworld paved the way for a rigorous and detailed programme, termed the Mapping the Underworld Location Project, which was funded by the Engineering and Physical Sciences Research Council (EPSRC), along with in-kind funding from 34 formal practitioner partners.

Our researchers successfully come together with practitioners to understand the needs of industry and develop a facility that has far-reaching implications for industry standards and safety.

Being able to map the vast network of buried utility pipes and cables without digging holes in the ground is faster, less disruptive, safer and more cost-effective. It will also allow engineers to predict how the ground, in its present, possibly altered condition will react if a trench is dug at a particular point in a particular road.

Railways

The UK rail industry has a clear vision for transforming the railways in the coming decades and we are at the heart of that transformation. As a world-leading centre, many of the vital research requirements contained in the latest UK Rail Technical Strategy are being carried out in our laboratories – and then transferred to railways across the globe.

The vision is to initiate a step change in performance to satisfy existing rail customers and attract new passenger and freight business. To do this, we are helping the industry to improve its performance by eradicating perennial problems, including track failures, cutting costs and becoming more resilient and energy-efficient.

Bringing together a multi-disciplinary team from across the University – along with other universities and partners in national and international industry – our focus is to address fundamental railway engineering problems. These range from line-side signalling and safety to frequent unplanned maintenance and service interruptions due to product failure or extreme weather conditions. We combine analysis, simulation and measurement to find ways to counter these difficulties in the long-term.

As well as solving existing problems, we work with organisations around the world, including in the US, China and Japan, to develop new train and railway system designs, through research, consultancy and professional development. Several universities conduct railway research, but we are the only one in the UK that covers the entire engineering spectrum, using pioneering technologies to find solutions to obstacles in the labs and on trains and rail networks around the world.

To limit disruption to services when one train is running late, we have developed automatic route-setting for areas of high traffic density and a method for dynamic rescheduling following service disruption of main-line railway operations.

We have designed the 'single train simulator' to generate a power-versus-time profile for an electric train on a particular journey. This is now being used around the world and can advise drivers on how best to drive trains on specific routes in order to conserve energy. For diesel trains, simulations we have carried out for the Department for Transport show that up to 20 per cent of energy can be saved through the use of hybrid braking systems.

We work on winter preparation with Network Rail to find effective ways to overcome problems caused by ice and snow, such as developing chemical products. We have devised a computerised in-service third rail condition monitoring system to measure the forces and movements of the third rail, which is now being tested on a Southern Railway train.

We have devised a 'robot train' that travels round the track spotting faults, generating a map which details the precise location of the problems. This is highly effective and hugely cost-effective because it saves on manpower and identifies faults before they become failures.

Our innovative approach to research includes a 'spinning rail', measuring about 4.5 metres in diameter and capable of notching up a speed of 80 km/h, which equates to two laps per second. Combining many different technologies, this enables us to collect a raft of data very quickly in terms of novel fault detection, such as cracks in rails at high speed. Because the temperature in the lab can go to as low as -58°C, it helps us with extreme weather analysis and problem-solving.

Hydrogen and Fuel Cells

Quieter, cleaner, zippier and cheaper to run, hydrogen-fuelled cars as for example developed here at Birmingham are set to revolutionise the motor industry. And it's not only cars – we are also developing fuel cell systems for trains, planes, ships and rail buses. In fact, we are the only UK research centre looking at all aspects of how hydrogen can be harnessed to create a greener future.

Hydrogen cars cut carbon emissions through the use of fuel cell technology which converts hydrogen's chemical energy into electricity through a chemical reaction. They only emit water into the atmosphere and can already be competitive to petrol or diesel models.

Replacing fossil fuels with alternative energy sources is vitally important if we are to cut carbon emissions. But powering vehicles – as well as domestic heating and lighting systems and electrical devices – with the likes of hydrogen and methanol will become a reality only if they can be proven to be reliable, robust and cost-effective.

And that is what we are doing here at the centre: from basic research on fuel cells to more complex work on the integration of green energy systems into existing transport vehicles, we are road testing the sustainable production, storage and commercial application of hydrogen and other green energy sources.

The internationally acclaimed centre is also working on the design and production of fuel cell equipment various mobile and portable applications – replacing batteries.

We manufacture our own fuel cells and test and optimise them in our laboratories. Our five-strong fleet of hydrogen cars has gone through a series of improvements and the next generation will soon be trialled on the streets of Birmingham.

The centre is home to the UK's first public hydrogen filling station and there are now several others around the country – which is crucial for the commercial success of fuel cell cars. Our hydrogen-powered house, a few miles from the centre, uses a hydrogen fuel cell Combined Heat and Power system.

The centre was awarded a grant to create and run a doctoral training centre in hydrogen, fuel cells and their applications in 2008, the first of its kind in the UK; the centre is currently running in its fifth year and is currently looking at extending operations to 2022.

A hydrogen-powered canal boat has been built on campus, powered by a combination of a metal hydride solid-state hydrogen store, a proton exchange membrane fuel cell, a lead acid battery stack and an NdFeB permanent magnet electric motor.

Energy

One of the greatest challenges the UK faces revolves around energy. The drive towards decarbonisation – reducing greenhouse gas emissions – requires changing the way we produce electricity. It also means electrification of transport and heat. In the near future electricity production using coal will become uneconomic, a fuel which provides about 40% of the current electricity production. The government strategy is to replace some of this by renewable sources, for example wind power, and new nuclear power stations.

One of the challenges of sources such as wind is what to do when the wind does not blow. The other problem is what to do when the wind is blowing and providing more electricity than required. Currently the surplus is dumped. Clearly the solution to the latter is to find ways of storing the excess to be used at times of low production. Currently energy storage is limited to sources such as hydroelectric plants – of which there are few. Other approaches are urgently required.

Birmingham is making important contributions to both nuclear energy and energy storage.

For half a century, we have been at the vanguard of the UK's nuclear research and education. Our work has been fundamental to the country's retention of its nuclear industry and we have led the education of nuclear engineers and scientists.

We have provided capital and infrastructure in order to expand further the University's nuclear expertise and capacity. We are also making significant investments in the area of nuclear engineering, waste management and decommissioning.

In energy storage we are working to develop new approaches which could provide technological solutions to the intermittency of wind. We are helping develop cryogenic energy storage, where electricity is used to liquefy nitrogen gas (essentially air) – this is where energy is stored. The energy is then released by allowing the liquid nitrogen to boil and turn into gas, expanding dramatically. This expansion may be used to drive a turbine, thus generating electricity.

Our research extends to areas such as bio fuels, powertrain systems and novel energy carriers, as well as more energy-efficient manufacturing. The energy challenge is global. Understanding the issues and finding solutions is at the heart of our research and education here at the University.

Through collaborations with the Universities of Nottingham and Loughborough, we established the Midlands Energy Consortium (MEC), which hosts the UK Energy Technologies Institute. The wealth of complementary expertise within the MEC has resulted in it leading three energy-related national centres for doctoral training, as well as hosting the Higher Education Funding Council for England-funded Midlands Energy Graduate School. This aims to broaden the wider energy knowledge of our research-led and taught postgraduates to help meet the growing demand in the UK for more highly-trained low carbon technologies researchers.

Our Policy Commission, chaired by Lord Hunt of Kings Heath, recently presented a report on nuclear power, which advocated a 'road map' to stall the 'sense of drift' in UK energy policy. It called for public consultation, greater cooperation between government and industry and government-led training and education to ensure a suitably skilled workforce, to meet challenges such as the threat of an energy crisis and climate change.

Together with Nottingham, we have established an active and growing research and education presence in Brazil, creating collaborations to develop energy-related technologies such as next-generation quantum sensors for oil discovery and well-management and material performance characterisation for deep oil extraction pipelines.

We are a partner in the Centre for Low Carbon Futures (CLCF), a joint project with the Universities of Leeds, Sheffield, Hull and York. This reflects our focus on challenges related to energy storage, storing wrong-time energy from renewable generation and balancing the grid when required. We have provided leadership in understanding the pathways for energy storage in the UK and are supporting the creation of a CLCF-China Centre for energy storage technology development and integration.

As a civic university, we also look to have an impact closer to home: Collaborating with the University of Leeds and funded by the Engineering and Physical Sciences Research Council, we have carried out a mini-Stern review of Birmingham and the wider region, to support the City in its vision to reduce its carbon footprint by 60 per cent by 2027.

Robotics and Human Interface Technologies

The fusion of state-of-the-art artificial intelligence with robotic systems is opening up new opportunities in medical surgery, autonomous vehicles, manufacturing and work in hazardous environments such as decommissioning of nuclear facilities – where humans cannot go. In less than a decade, we have made giant steps towards bringing robotic machines 'to life' as never before.

Robots are not new, but traditional factory robots perform one task repetitively and are unable to cope with change, novelty and uncertainty. At Birmingham, we are developing robots that are 'smart' enough to multi-task, and that have much better perception, reasoning and learning abilities. We are now patenting some of these cutting-edge technologies for commercial use.

We have successfully built robots with such advanced artificial intelligence that they can not only track down specific objects in a building, but can 'think' for themselves and explain their failures when they fail to complete their task. These robots can even search out humans to ask questions to try to resolve the problem.

We have also started working on making robots less robotic! By this we mean we are trying to create more dexterous humanoids; machines that are better able to grasp and manipulate objects so they can engage in more complex tasks. This involves making our robots compliant, and endowing them with improved vision and touch.

These latest breeds of robot, which use rationality, common sense and an ability to reason about uncertainty to plan and carry out a raft of activities, are likely to be used for tasks as diverse as border surveillance, land survey, agriculture and stroke rehabilitation.

We undertake world-class, high-impact, human-centred research and development in Virtual and Augmented Reality, 'serious games' and multimodal technologies for training and visualisation solutions in the fields of defence, healthcare and cultural heritage. In the defence sector for example, the SubSafe games-based simulation project culminated in an extensive experimental programme, exposing real naval recruits to a unique virtual submarine environment. The experiments generated significant results in favour of adopting interactive 3D technologies to enhance submarine safety awareness, and these results have since influenced the Royal Navy and its Australian and Canadian counterparts to adopt similar technologies for future submarine training. Operators of the advanced British bomb disposal robot, CUTLASS, based in the UK, Gibraltar and Cyprus, are also now benefiting from unique simulation technologies developed by us.

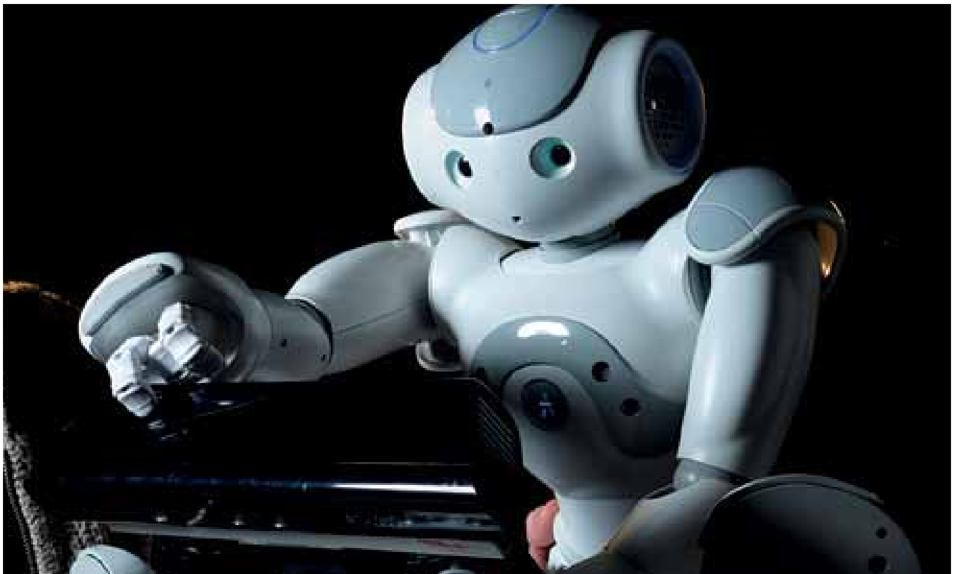
In little more than eight years, our robots have progressed from an automaton named Mr Chips, which was able to visually identify objects and answer simple questions with three possible responses, to Curious George, which engages in a complex conversation with a human to find out more about its world. This is part of a huge leap forward in the development of 'cognitive robotics' over the past decade.

Our PacMan project takes robotic manipulation of objects a step further by enabling them to 'learn' how objects are made up of parts, and to use this new knowledge to manipulate objects in new ways.

The CoDyCo (Whole-body Compliant and Dynamical Contacts in Cognitive Humanoids) project, focuses on how to programme walking robots so that their motors have a certain amount of 'floppiness' in them – as humans do – to make them more dexterous.

STRANDS (Spatio-Temporal Representations and Activities for Cognitive Control in Long-Term Scenarios) is a project coordinated in the IRLab. It explores how a mobile robot can perform intelligent autonomous behaviour for long periods (up to four months) in human-populated environments.

Our CogX (Cognitive Systems that Self-Understand and Self-Extend) project saw the development of 'Dora the Explorer' and 'Curious George'. Dora is able to map buildings, find objects, and works to perform tasks given by a human. George is a robot that asks questions to satisfy its curiosity about its world.



Cyber Privacy

Imagine walking into a crowded room and recognising everyone gathered there – even though you've never met them before. How great would it be to know who was a lottery winner and who was a convicted fraudster?

Thanks to the rapid advancement of technology, this isn't a far-fetched scenario. Face recognition systems are already in use and the first version of Google Glass 'spectacles' are due out soon. But is it a scenario we want?

Even now, we live in a world where computers record our movements and actions. Our mobile phones track where we go and who we speak to; CCTV cameras capture us as we go shopping. With more sensors and devices springing up all the time, ordinary people's privacy is being increasingly invaded.

As a society, we haven't yet decided what we want to do with this mounting collection of data. The general consensus is that our right to privacy should be balanced with law enforcers' right to uncover crime and terrorist activity.

Our computer scientists are working on finding technologies that would support this balance; for example, we are working on a system that would allow the security services to read a proportion of people's emails, but without knowing who wrote them. Only if they spotted something sinister would they be able to trace the sender and recipient. Crucially, the number of emails they had read and the number of times they had uncovered the sender and recipient, and the crimes solved as a result would all be publicly verifiable.

In this way, we believe our work will prove invaluable as a way of helping to solve crime and prevent terror attacks, while at the same time limiting the authorities' ability to 'spy' on its citizens.

What we still need to decide, as a society, is whether we want a stranger to know everything about us before we've even said 'hello'.

We have devised an e-voting system that can identify and monitor any votes that may have been carried out under coercion. Called Caveat Coercitor, the system would alert authorities to such votes. For instance, a coercer might change a legitimate vote by installing malware on the victim's computer, or vote on their behalf by stealing their voting password from the post. This system would enable the authorities to analyse the impact of such votes on the election result. The coercers could then be traced and prosecuted.

We have proved that a lot of 'smart' technology is, in fact, not-so-smart because it isn't secure: we have used reverse engineering and cryptanalysis to crack the codes of smart cards used for controlling access to official buildings and transport systems around the world, thereby demonstrating they could be cloned by criminals.

We have used reverse engineering and cryptanalysis to demonstrate that the Basic Access Control protocol on e-passports was flawed, leaving it vulnerable to a replay attack that makes it possible to trace a passport.

We are developing more secure access control systems (ACSs) than the ones currently in place. ACSs are used to regulate access to resources such as files, database entries and web pages. Because computers are increasingly interconnected, it's important to prevent malicious users from gaining access to these resources.

In collaboration with the Universities of Glasgow and Liverpool, we are working on the Verifying Interoperability Requirements in Pervasive Systems project, funded by the Engineering and Physical Sciences Research Council.

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