IOP Institute of Physics
East Anglia Branch

THE CAVENDISH LABORATORY

&

THE CAMBRIDGE PHYSICS CENTRE

Present the

2014
PHYSICS AT WORK EXHIBITION

at the Cavendish Laboratory,
Madingley Road, Cambridge

On

Tuesday 23rd September
Wednesday 24th September
Thursday 25th September

Organised by:

Dr. Lisa Jardine-Wright and Elizabeth Bateman
Educational Outreach Department, Cavendish Laboratory

Facilities and Technical Assistance:

The Cavendish Laboratory

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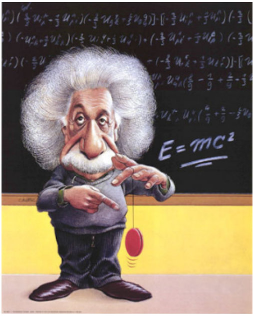
PHYSICS AT WORK 2014

Exciting discoveries



The Physics at Work Exhibition showcases many uses of physics in everyday life, along with applications of physics in research and industry. During your visit you will have the opportunity to gain first-hand experience of what is happening in the world of science today. Each of the exhibits will be presented by people working at the cutting-edge of research and development; please do not hesitate to ask them any questions you like – the exhibitors are here to provide answers!

Looking to the future

Many of those that have attended Physics at Work Exhibitions in the past have gone on to have physics-based careers in industry, commerce and research. If you are already thinking about a career in science, technology or engineering, the exhibition will give you some further ideas about the kind of jobs you can do if you have qualifications in science.

Inside this booklet, alongside the information about each exhibit, you will see a short profile of some of this year's presenters. Each profile includes information about their education and training, what their job involves on a day to day basis, and other careers that they have had or considered along the way. Take a few minutes to have a look at the breadth of opportunities available to physicists.

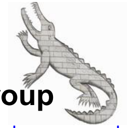
If you don't intend to take up science professionally a visit to the Physics at Work Exhibition may still be fascinating and valuable. We are all influenced on a daily basis by scientific discoveries and advances - the first compact disc players and TV mobile phones were demonstrated at Physics at Work Exhibitions!

The 2014 Physics at Work Exhibition will give you insight into the next generation of scientific achievements – have fun!

For more information about the types of jobs you can do if you have scientific qualifications visit: http://www.physics.org

Cavendish Laboratory

1. Semiconductor Physics Research Group



http://www.sp.phy.cam.ac.uk

Electricity seems very simple - you just flick a switch and there it is – but how often have you thought about what is happening to the electrons which make up that electricity?

The electrons' behaviour can change depending on what material they are in. Materials can be divided into three categories according to their ability to conduct electrons. In insulators, such as rubber and plastic, charge does not flow at all. In conductors, such as metals, electric charge can flow easily. In semiconductors, such as doped Silicon, the ability of the material to permit charge flow can be controlled. Thus semiconductors can range from insulating to conducting. This can be very useful; computer processors are based on the ability to switch currents on and off quickly. Semiconductor transistors are well suited to this task, being able to go from conducting to insulating by simply applying a small voltage to a special terminal.

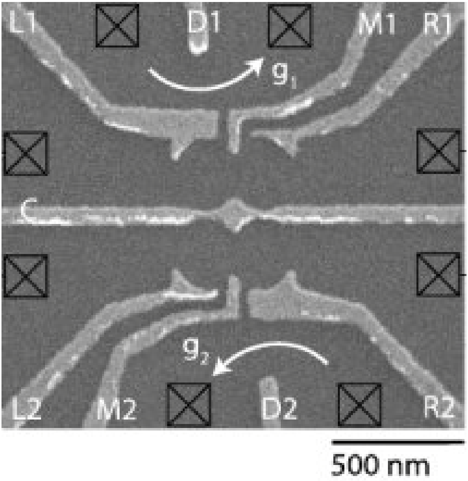
In the Semiconductor Physics group, we design, make and carry out experiments on new kinds of electrical devices to find out how electrons behave, and how we can control them. In the larger scope, beyond the research, our work leads to faster, more energy-efficient semiconductor devices and even brand new ones.

Few dimensions and quantum mechanics

Our group specialises in the physics of electrons confined to two, one or zero dimensions. Electrons can be made to travel in two dimensions by stacking layers of different semiconductors, in effect trapping the electrons at the boundaries between the layers. We can also apply electric fields on the stacked layers of semiconductors to force the electrons to travel only along one direction or not allow them to move in any dimension at all, which gives us quantum dots.

Some of us study semiconducting materials that are naturally two- or one-dimensional, such as graphene (single layers of graphite) or carbon nanotubes (rolled up graphene). Others in the group investigate how layered semiconductor structures turn electrons into photons (light particles), in particular making lasers that work at wavelengths not easily produced by the usual methods. Some of these wavelengths could be used to image people either for security or medical purposes and, unlike x-rays, are not harmful.

However we do it, the electron behaviour is very different compared to that in 3D. Quantum mechanics starts to take over from classical physics, with lots of strange effects such as quantisation (measured quantities can only be multiples of a certain value) and wave-particle duality (for example, electrons creating diffraction patterns).



🡐 ***Figure 1:*** *Quantum dots in a layered semiconductor (GaAs/AlGaAs) structure. The light regions are metal; when a voltage is applied the electric field beneath the metal forces the electrons at the layer boundary to travel in the dark regions. The black crosses represent measurement wires.*

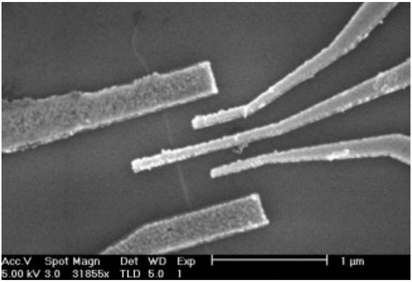
Fabricating new kinds of device

The devices we make have to be very small, down to just a few millionths of a millimetre high or wide. This is about a thousand times smaller than a dust particle, so they have to be fabricated in a clean room where virtually all the dust particles have been removed.

Layered structures are deposited a single atomic layer at a time by molecular beam epitaxy (MBE), where a beam of particles is fired at a pre-grown crystal with a known configuration of atoms on its surface. This is done in an ultra high vacuum so no unwanted atoms can change the properties of the finished structure.

Figure 2: ➔

A carbon nanotube double quantum dot. The nanotube is just visible between the larger contacts. The contacts which don't touch the nanotube are used to change the electric field in the two sections separately. The 'fingers' of metal are over 1000x thinner than a human hair.



Name: Mrs Melanie Tribble

Position: Research Associate

Company: Cavendish Laboratory

Educated at: Lordswood Girls' School, Birmingham

A-levels: Physics, Chemistry, Maths, Computer Studies

University: St. Hilda's College, Oxford

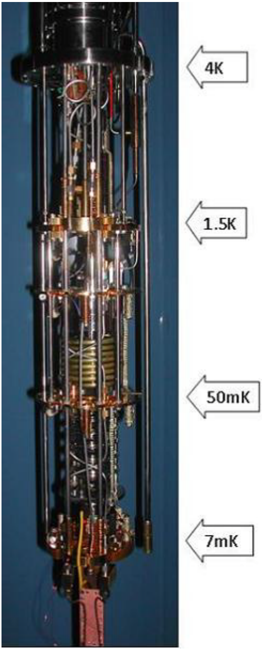
Qualifications: BA Hons Physics

Current job: 1992-date Semiconductor Physics Group, Physics Department, University of Cambridge. I am responsible for the maintenance of the SP cleanroom including repairing equipment, ordering supplies, managing cleanroom suits and helping people outside of SP who want to use our cleanroom. I also assess the quality of gallium arsenide wafers grown in SP's molecular beam epitaxy systems by making and testing devices from them.

Previous job history: 1989-1991 Account Representative, Dorothy Millman Marketing Services, Toronto, Canada. I spent two years promoting store credit cards.

1986-1989 AEA Technology, Harwell. I worked in the Solid State Chemistry Group of the Materials Development Division. The work of this Group consisted of the development of solid state gas sensors, batteries and optics. I worked principally in the area of fibre optics

Interests: I collect antique vesta boxes and old postcards. I enjoy making dolls' house miniatures and I can occasionally be heard ringing church bells.



🡐 ***Figure 3:*** *A dilution refrigerator, one of the pieces of experimental apparatus we use to measure our devices at very low temperatures. This image is labelled with the temperature each part of the fridge reaches (absolute zero = 0K (Kelvin), one mK = one thousandth of a degree Celsius). Devices are mounted below the bottom of the picture.*

Measuring at very low temperatures

Most of the experiments we do in Semiconductor Physics are resistance measurements, observing the effects of magnetic and electric fields, temperature changes, and AC voltage frequencies on the electrons flowing through our devices.

At higher temperatures, quantum mechanical effects on the measured resistance are overshadowed by the contribution from electrons colliding with the oscillating nuclei of the material. In order to see quantum mechanical effects, we have to cool our devices down to very low temperatures, usually between a few thousandths and a few hundredths of a degree above absolute zero. To get to such low temperatures, measurements are carried out in cryostats, which are essentially very efficient refrigerators that use liquid nitrogen and liquid helium as refrigerants. By observing how electrons behave under certain electric and magnetic fields at low temperature we can use the scientific method to work towards bringing this behaviour towards room temperature.

2. The Technology Partnership

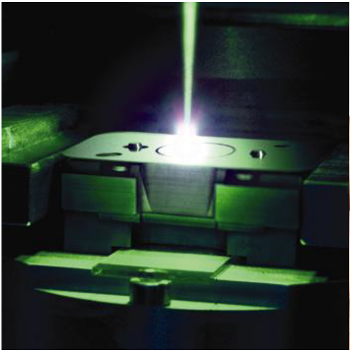
http://www.ttp.com

Innovation

The Technology Partnership, TTP, was founded in 1987, and for over 25 years has established a reputation as Europe's leading independent Technology and Product Development organisation.

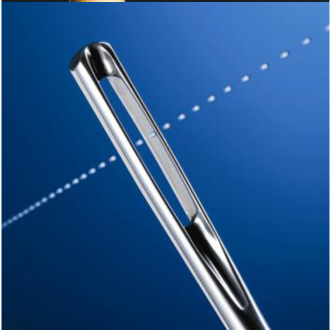
TTP has been responsible for some world-leading developments in fields as diverse as wireless communications and digital printing through to drug delivery.

We work in partnership with our clients to bring new products to market, creating new business from advances in technology. We are co-operating with some of the most famous companies in the world – companies that share our vision and understand the true value of intellectual property. Companies like: Airbus; Bayer; Cadbury Schweppes; Fuji Film; GSK; Hewlett Packard; Philips; Panasonic; Unilever; Xerox and many others, too numerous to list.



Physicists play a major role at TTP, and can work on a wide range of projects from printing and laser technology through to confectionery packaging.

Electronic Aerosols

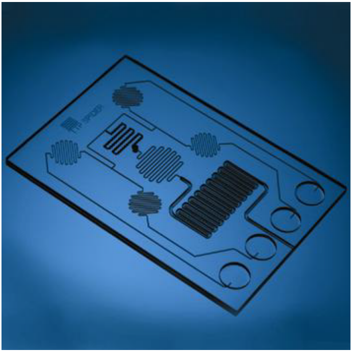


One example of physics at work is TTP’s development of ‘electronic aerosol’ technology and products based upon it. Conventionally an aerosol is produced by ejecting a liquid at high velocity through a fine nozzle. The flow is turbulent causing small localised pressure fluctuations in the liquid; and these lead to the break-up of the jet into a stream of small droplets of relatively uncontrolled droplet size. In domestic spray products, such as aerosol cans, the liquid ejected is typically a solution of a product (e.g. air freshener, insecticide) in a high vapour-pressure propellant liquid. This is environmentally unattractive.

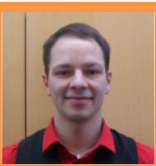
By contrast, TTP’s ‘electronic aerosol’ technology employs a piezoelectric actuator to oscillate a perforated membrane, contacting the liquid to be sprayed, at ultrasonic frequencies. The high frequency oscillation causes oscillatory pressure fluctuations that eject the liquid through the holes. One droplet is ejected per hole per cycle. Using many holes creates a strong spray. The droplet size is primarily determined by perforation size. The result is a low velocity spray of droplets of very well controlled size and direction without the use of harmful propellants.

Applications range from drug delivery to consumer products such as hairspray and deodorant.

Microfluidic Technology



A second example of physics at work is TTP's microchemistry platform, a patented microfluidic system that allows complex applications of laboratory biochemistry to be undertaken on a miniaturised, low cost disposable card. By harnessing cutting edge micro-fabrication methods and knowledge of fluidic flow on a micron scale, such devices are becoming a reality and enable small handheld portable diagnostic systems. Used in Ambulances and GP surgeries, these devices will allow early detection of time-critical illnesses such as heart disease.



Name: Dr Matthias Ediger

Position: Technology Consultant

Educated at: Gymnasium Burgwedel, Germany

A-levels (or equivalent): Maths, Physics, Geography, German

University: University of Hannover, Germany and Heriot-Watt University, Edinburgh

Qualifications: Physics Diploma, PhD in Physics

My day to day work involves... managing projects, finances and clients to deliver proposed objectives. This involves inventing devices or technologies, designing experiments to measure their quantities and writing reports on their performance for the envisioned use. It can also lead to the same ideas being used in another project and for a completely different client to solve problems in a new way.

Other experience or previous professions: Corporate research and development on high pressure discharge lamps and postdoctoral research at the Cavendish Laboratory into magneto-optics of nanostructures.

The best thing about my job is... the variety of problems I have to solve on different projects at any one time.

The thing I like least about my job is... ultimate control over the project lies with the client

Other careers considered: High school teacher, professor, and dancer.

Name: Dr Antony Rix

Position: Senior Consultant & Project Manager

Educated at: Manchester Grammar School

A-levels (or equivalent): Maths, Further Maths, Physics, Chemistry

University: Christ's College, Cambridge (MEng) and Edinburgh University (PhD)

Qualifications: MEng Electrical & Information Sciences, PhD

Electronic Engineering (Perceptual techniques in audio quality assessment).

My day to day work involves... developing new types of radio technology from basic concept through to manufactured product. I work with customers to create and evaluate concepts for new technologies, design and run research projects to implement and test the ideas, and manage the whole process of business development, contracts, electronics and software development, production engineering and transfer. A reasonable amount of international travel to meet customers and attend conferences.

Other experience or previous professions: Corporate research, founder of a successful dot-com start up.

The best thing about my job is... designing things that make a real difference to their users.

The thing I like least about my job is... Legal negotiations

Other careers considered: Academia

Name: Dr David Cottenden

Position: Consultant Physicist

Educated in: *St Thomas More and Sharnbrook* Upper Schools, Bedford

A-levels (or equivalent): Maths, Further Maths, Physics, Chemistry

University: Churchill College, Cambridge

Qualifications: MA (Cantab) physics / maths, MMath, PGCE secondary maths, PhD in biotribology

My day to day work involves... developing medical devices of various types on behalf of many different large and small companies internationally. This involves experimental and theoretical (both pen and paper and computational) work, as well as creative engineering design, and importantly also interacting with clients to communicate progress and agree future direction.

Other experience or previous professions: academia, teaching.

The best thing about my job is... the variety and continual challenge of doing something new every day.

The thing I like least about my job is... The repetitive phase of experiments – much more fun when things are still going wrong!

Other careers considered: Teaching and academia!

University of Cambridge

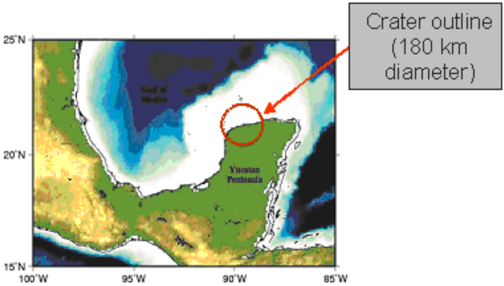
3. Earth Sciences (Dept. Of),

Bullard Laboratory

http://www.esc.cam.ac.uk

Seismics - A look at Global Catastrophe

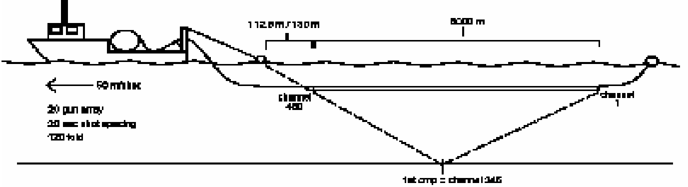
Sixty-five million years ago a 10 km diameter meteor crashed into the Yucatan Peninsula of Mexico leaving a 200 km wide crater. This crater is known as the Chicxulub crater (it is named after the small fishing village that is now at its centre). It is one of only three known impact craters on Earth with diameters larger than 150 km. Seventy percent of the species on the Earth including the dinosaurs went extinct during the time that this impact occurred, and there is strong evidence that the red hot dust thrown up by the impact was responsible - having effectively barbecued anything on the surface of the earth! The area around the impact point is now completely flat under a 1 km layer of limestone, and the crater was first identified by gravity surveys that revealed a strong concentric pattern. More recently seismic studies have been used to investigate the structure of the earth's crust around the crater, with a view to getting a better understanding of the size and direction of the impact and of the disturbances caused.

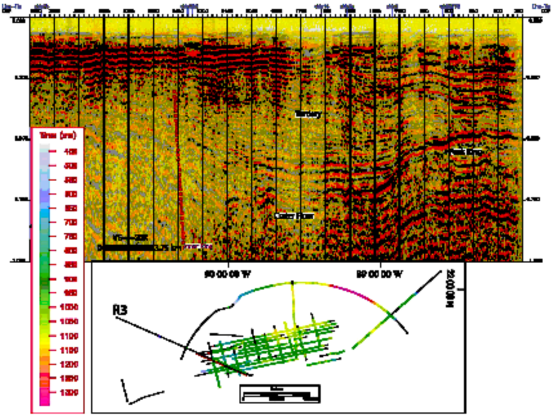


The University of Cambridge has recently been involved in the largest seismic survey of the crater, involving over a month of seismic shooting and recording with hundreds of receivers on the seabed and on land. Preliminary results show the exciting sectional views of the crater, which we will be presenting.

As well as showing our hot-off-the-press scientific results, we explain the seismic technique using simple demonstrations of waves, and show how these can be built up into profiles that are virtual cross sections through the earth's crust. The resulting technique is by far the most powerful tool we have for probing the outer layers of the solid earth. As well as yielding unique insights into the earth's history, the entire oil and gas industry is based on the use of seismics to locate and identify reservoirs and track the movement of oil and gas during extraction. The enormous economic importance of the industry makes it a major employer of scientists and technologists, with many exciting and well-paid job opportunities.

The Seismic Technique

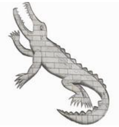




Preliminary seismic section from 2007 experiment.

Cavendish Laboratory

4. Astrophysics Research Group

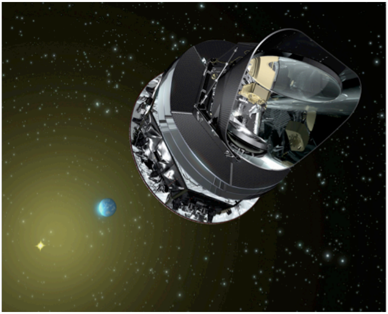


http://www.mrao.cam.ac.uk

Astrophysics:

Astrophysics is all about making measurements and predictions about how the Universe fits together. Our research group involves theorists, who use complex mathematics to solve the equations of the Universe, engineers who build telescopes and design experiments to collect data from the Universe and astronomers who study the data we gather and try to see if the theorists were right or wrong!

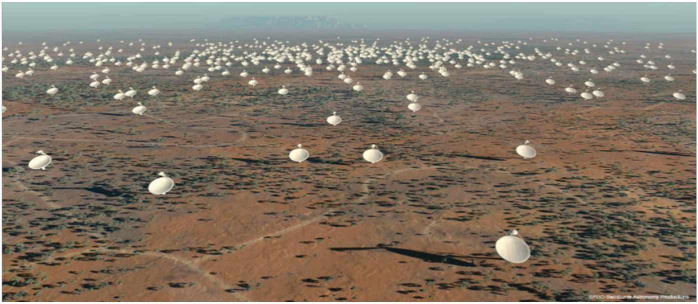
The Astrophysics group at the Cavendish has historically been involved closely with radio telescopes – that is telescopes that pick up radio waves from outer space. These waves are naturally generated and don't (necessarily) come from distant civilizations, but they do tell us a lot about the physics in different parts of the Universe.



🡅 ***Figure 1:*** *Artist's impression of the Planck satellite showing the Earth and Sun in the background. Credit: European Space Agency*

We are currently involved in several telescope projects. One, the Planck satellite was fired into space in May 2009 and is now sitting at the so-called "L2" point, 1.5 million km from Earth. Planck's job is to map radiation patterns from when the Universe was very young and hot, when it was only about 300,000 years old. The first images are being beamed back to Earth now.

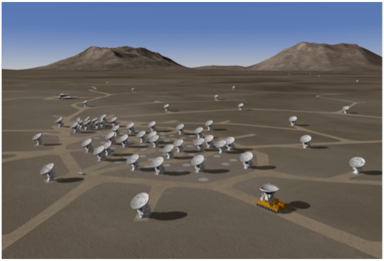
We are also working on a telescope called "The Square Kilometre Array" or SKA. This will be a huge ground-based radio telescope with over a million square metres of collecting area, making it by far the most sensitive telescope ever built. The SKA will have up to 3,000 dishes, each 15m in diameter. By



↑ ***Figure 2:*** *Rendition of what the SKA might look like, with up to 3,000 dishes spread across the desert. Credit: SPDO / Swinburne Astronomy Productions*

comparing the signals from different dishes in the array astronomers are able to build up very detailed maps of the objects in the sky that shine at radio wavelengths.

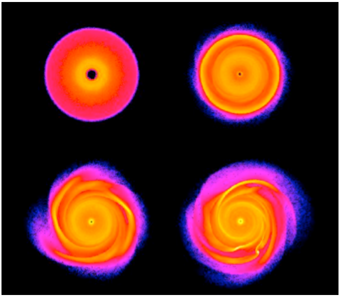
One of the aims for the SKA is to build up a 3-D map of the positions of a billion (a thousand million) galaxies in the sky. The positions of these objects will span a range of distances from Earth, so, because the radio light from distant objects will have taken time to get to Earth, we will be looking back in time. We can then use our 3-D map to see if the patterns of objects are different for the nearby objects (when the Universe was almost as old as it is now) and distant objects (when the Universe was much younger). This will tell us how the Universe has been changing as it gets older.



↑ ***Figure 3****: What the ALMA array will look like, with 66 high-precision dishes. Credit: ALMA/ESO/NRAO/NAOJ*

We also work on another new telescope called ALMA, which is being built in Chile. The 66 dishes of ALMA work at relatively high radio frequencies. ALMA will be very good at studying the light from "proto-planetary disks" which are the swirling masses of dust, ice and rock that appear as stars form, and which ultimately lead to the formation of planets.

ALMA will help us to understand the processes of planet formation, which is very important to see how unique our own solar system (and planet Earth) is, and how likely it might be that there are other planets just like our own, and who knows, maybe with intelligent life on them.



🡅 ***Figure 4:*** *Simulation of planets forming out of a swirling disk of matter orbiting a new star. (Credit: Professor T Quinn, University of Washington)*

Some web links:

Chandra X-Ray observatory (lovely pictures): http://chandra.harvard.edu/

Planck Satellite mission: http://www.sciops.esa.int/index.php?project=PLANCK

SKA Telescope: http://www.skatelescope.org/

Name: Eloy de Lera Acedo

Position: Senior Research Associate

Educated in: Spain

A-levels: Physics, Biology, Mathematics

University: University Carlos III of Madrid

Qualifications: EngD in Communications technology

My day to day work involves: Designing the antennas and electronics for modern telescopes such as the SKA, testing them and creating models for the telescope calibration.

Other experience/previous professions: I have always worked on designing instrumentation for astrophysics.

The best thing about my job is: I love going to astronomical observatories around the world and seeing my designs working.

The thing I like least about my job is: Not being able to spend the whole working day researching new ways to design better telescopes.

Other careers considered: Physicist, Aeronautical engineer.

5. Atomic Weapons Establishment

http://www.awe.co.uk

Explosive Energy

The Atomic Weapons Establishment (AWE) plays a crucial role in the defence of the United Kingdom by providing and maintaining the country's nuclear deterrent. It also has a key role in supporting the Comprehensive Test Ban Treaty, counter terrorism and the country's national nuclear security. It is a centre of scientific and technical excellence, with world-leading experimental facilities and supercomputers.

Energy is a word that is often used incorrectly. There's a lot of talk about finding sources of "renewable energy" and "green energy". Whilst these are good things, energy isn't something we can create, it is a conserved quantity, meaning that across the entire universe the amount of energy is always the same. We can't create it, we can't destroy it, all we can do is convert it between various forms.

The conservation of energy can be proved from time invariance in quantum mechanics using Noether's theorem.

There are many different forms of energy. We will focus on stored energy (such as chemical), released energy (such as heat), and changing between the two. We can get different effects by controlling the release in different manners, or the same effect from two apparently unrelated methods.

When we talk about energy, we should also think about the density of the energy, and its time frame. When we focus energy into a smaller area (increasing its density) the difference is obvious.

Consider a magnifying glass focusing light from the sun onto paper, the same amount of light energy is present, just incident on a smaller area therefore higher density; it's the same with time. As an example, if you burn methane slowly we get a nicely controlled flame which can be used in a Bunsen burner, too fast and you may get an explosion.

This can be thought of as the density of energy, but only density in time not space. All you are doing is changing to a different dimension.

The largest objects we know that convert between different types of energy are stars. In the centre of stars, protons are fused together to form Helium nuclei. This releases vast amounts of energy that was previously stored as mass, so mass is really just a different form of energy.

Einstein's famous equation, $E=mc^2$, tells us that huge amounts of energy is stored as mass. The factor of c^2 is approximately $9x10^{16}$ m^2s^{-2}, that's 90 thousand million million. Energy can be converted from mass in nuclear fusion or nuclear fission. Even a small amount of material can release vast amounts of power.

With the aid of live demonstrations and video footage this presentation will look at the rapid release of stored energy, and the role of energy density within this. Please let us know if you're epileptic, have heart conditions or are afraid of loud noises.

Name: Dan Lewis

Position: Explosives Scientist

A-levels (or equivalent): Physics, Maths, Chemistry, Biology

University: University of Surrey – Undergrad, Defence Academy of the UK (Cranfield) – Masters.

Qualifications: MSc in Explosive Ordnance Engineering, BSc in Physics w/ Nuclear Astrophysics.

My day to day work involves... Testing and development of experimental high explosive formulations. Development of computer models that predict an explosives' response to various stimuli, computer models inform on what will work and what will not in terms of an explosive formulation.

Other experience or previous professions: Previous job working with high explosives and counter terrorism – Home Office.

The best thing about my job is... Working with a variety of diverse experts within the Explosives community and being able to develop unique ideas/experiments that can be developed into real world solutions.

Other careers considered: Returning to counter-terrorism and blast mitigation.

Name: Hardik Trivedi

Position: Design Engineer

Educated in: St Josephs College, London

A-levels (or equivalent): Maths, Physics, Biology and Chemistry

University: Queen Mary University of London

Qualifications: MEng in Aerospace Engineering

My day to day work involves... I continually use the knowledge that I have developed throughout my education on the job. I help to deliver innovative design solutions to components and devices using specialist software and manufacturing technologies. I lead in presentations given to my peers on a range of topics about the projects I am involved with.

The best thing about my job is... : I am involved in a number of diverse projects so there is never a dull moment in the day. I get to do technical work with a team of professionals using cutting edge technology.

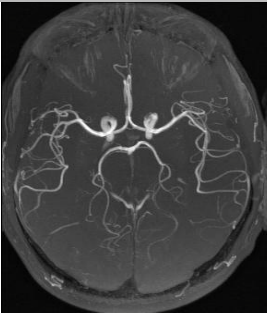
Other careers considered: Material Science, Biophysics.

6. Wolfson Brain Imaging Centre

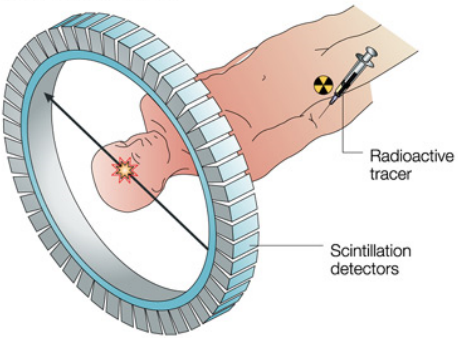
http://www.wbic.cam.ac.uk

Brain imaging

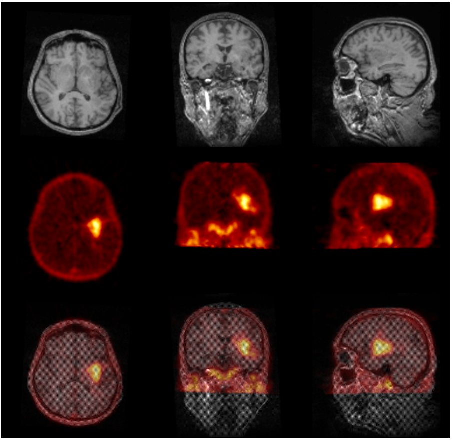
The brain has over 100 billion nerve cells and it is the most complex structure of the human body. There are many brain-related diseases and disorders. For example, Alzheimer's disease, addiction, head injuries, Huntington's disease, stroke, multiple sclerosis, depression and epilepsy are all brain diseases and disorders. Despite advances in brain research during the last ten years, disorders of the brain and central nervous system remain the nation's greatest cause of disability and account for the greatest number of prolonged care patients in hospitals. In our exhibit we will talk about two very useful tools used by brain researchers to understand how the brain works and to identify brain diseases and disorders - Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET).



🡅 ***Figure 1:*** *From top left (going clockwise): MRI image of human brain, MRI scanner and MRI angiography image of arterial blood flow.*



🡐 ***Figure 2:*** *PET data acquisition - detecting positron annihilation events from injected radiotracers.*



🡐 ***Figure 3****: MRI (top), PET (middle) and overlaid (bottom) images of stroke patient, showing PET tracer activity in affected area.*

For more information on volunteering for MRI studies:

- Centre for Speech, Language and the Brain
  https://csl.psychol.cam.ac.uk/volunteers/neuroimaging.html
- MRC Cognition and Brain Sciences Unit
  http://www.mrc-cbu.cam.ac.uk/take-part/

Name: Dr Marius Mada

Position: MRI Physicist

Educated in: Romania

A-levels (or equivalent): Maths, Physics, Chemistry

University: Technical University Cluj Napoca (BEng), Babes-Bolyai University (MSc), Universite Claude Bernard Lyon (MSc) and University of Nottingham (PhD)

Qualifications: BEng in Engineering and in Radiography, MSc in Medical Physics, PhD in functional MRI imaging

My day to day work involves... ensuring the MRI scanner is working at the optimum level for patients. This is done by scanning “phantoms” which comprise tubes filled with different gels or solutions and comparing the images we attain to the standard expected for the scanner. I also design new scanning protocols to be used in research studies, such as the development of MR elastography. In these research studies I often program new RF pulse sequences for the scanner to use and think about the best way to scan patients to maximise the information we can attain in each scan. I also interact with patients who have volunteered for research studies and scan them.

Other experience or previous professions: Medical equipment company dealing with therapeutical lasers and healthcare consultant for Siemens Romania.

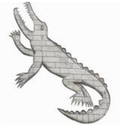
The best thing about my job is... developing new technology that has medical applications.

The thing I like least about my job is... waiting for the scanner to be fixed when it is broken

Other careers considered: Radiographer, Automation Engineer

Cavendish Laboratory

7. Team Crocodile: Fuel-Efficient Car



http://www.teamcrocodile.com

What is the best car to have?

There are a wide variety of cars on the road today, from the high-cost and high-speed Ferrari to the run-about Fiesta. The choice of car can depend on factors such as cost, colour, parking space required and safety. Until the end of the 1960s fuel efficiency was generally not considered important; petrol was cheap and plentiful. However, an oil crisis developed in the early 1970s, forcing the car industry and petrol companies to think about the possibility of only having access to a limited amount of petrol at high cost. Drivers began to think more about the cost of driving. In the 1980s and beyond, the effect of greenhouse gases, some of which are produced in part by car exhaust fumes, caused people to think more deeply about the pollution produced by vehicle use.

One answer to these problems lies in better fuel efficiency. The modern world cannot function without goods being transported along roads, and many people live a great distance from their place of work. Public transport can help many people, but it cannot solve every transport problem.

Table 1 shows comparisons between a high-speed racing car, a sports car, a standard family car and the Team Crocodile fuel-efficient car. Speed is not always the most important thing to look for when choosing a car; some cars cannot travel very far on the amount of petrol that an average family can afford.

How can we make a car more fuel-efficient?

To make a car more fuel-efficient we need to understand the scientific factors that affect the fuel-efficiency of the car, and have the technology to put this knowledge to use. The major factors that affect the fuel-efficiency of cars are:

- **Friction:** How much grip is needed to help the engine push the car along? Is there too much grip, slowing the car down? Are the car tyres made out of soft or hard rubber?

Figure 1: *Team Crocodile's Fuel-Efficient Car & Drivers*

- **Aerodynamics:** What is the best shape for a high-efficiency car? What affects the stability of the car?
- **Weight and Power:** What is the most appropriate engine size? A large engine may give extra power, but is all that extra weight a good thing?
- **Technology:** What are the best materials to use for different parts of the car (e.g. tyres, body shell, axle and bearings)? Why?

Type of Car	Maximum Speed (mph)	Efficiency (mpg)
Formula 1 Racer	185	2
Sports Car	130	35
Family Saloon	90	50
Team Crocodile Fuel-Efficient Car	35	3,894
Fuel Efficient World Record 2005	25	11,254

Table 1: *Maximum speed and fuel efficiency for different types of car*

The Team Crocodile Fuel-Efficient Car

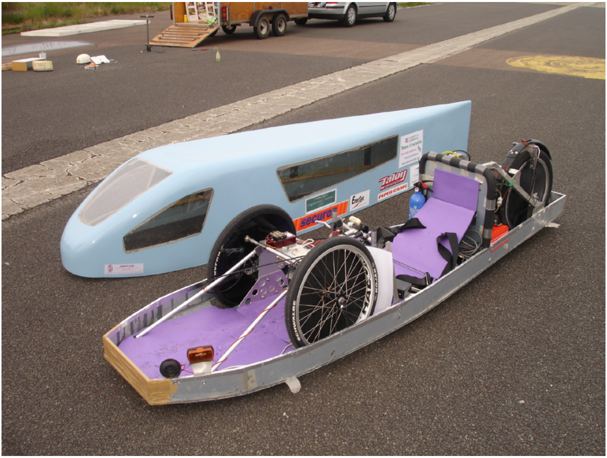


Figure 2: *Inside Team Crocodile's fuel-efficient car.*

Rik Balsod, a research assistant at the Cavendish Laboratory, instigated the Team Crocodile project in 1996. The aim of the Team Crocodile project was to provide a learning tool to enable students in schools to get hands on engineering experience, share ideas and understand the importance of team work.

The Team Crocodile car was constructed with a great deal of help from the University of Cambridge Engineering Department, where Dr. Alan Organ and his colleagues devise student design projects to develop specific chassis structures and body shell aerodynamics. Their models were tested in wind tunnels and the final design was then constructed by the technical staff. The car chassis is made from 10mm honeycomb aircraft specification material to give a light but strong construction. The body shell is made from fibreglass, which is light and smooth and easily shaped. The tyres are Michelin (20" x 1¾") and the brakes are calliper brakes, similar to those found on bicycles.

The Shell Eco-Marathon

The Shell Eco-Marathon was a competition that was held in the UK for over 30 years until 2010. The challenge of the competition was to build a vehicle powered by an internal combustion engine to carry a passenger as far as possible on one gallon of fuel. It was a world-renowned international competition in which schools, colleges, universities, companies and individuals took part.

In the competition cars were required to drive at an average speed of at least 15 miles per hour for seven laps around Rockingham racetrack, which is a total distance of 10 miles. At the end of the seven laps the amount of fuel used was measured. The fuel-efficiency of the car could then be calculated.

In 1996, our first competition attempt, Team Crocodile achieved 2nd place in the "newcomers" category. The efficiency of the Team Crocodile car was found to be 2,101 miles per gallon, representing an overall position of 9th in the UK, and 22nd in the world. The winning team had over £1,200,000 support from the car industry and achieved an efficiency of 9,472 miles per gallon. In 2002, Team Crocodile were placed 5th in UK, and 6th in the world, having increased their fuel-efficiency to 2,712 miles per gallon (winning team achieved an efficiency of 10,240 miles per gallon). In 2005, the world record was broken by a Japanese team with 11,254 miles per gallon and a budget of £3,200,000.

Our Team Crocodile project is exhibited during National Science Week, Physics at Work and on bespoke school trips. One of our best achievements has been to inspire 97 students into apprenticeships and industrial studies, 37 of which were girls with 23 going on to graduate from University. Of the 60 boys, 43 went on to graduate. Two girls were successful in receiving Masters degrees and two boys their PhDs! The results of our entries in competitions in 2014 will be available at the Physics at Work 2014 Exhibition, and on our website.

Team Crocodile is still very much active, despite the Shell Eco Marathon event being stopped in the UK in 2010. A few of the members of the teams have managed to carry on the tradition so youngsters can still compete - now at a new venue, Mallory Park Racing Circuit.

University of Cambridge

8. Material Science & Metallurgy (Dept. Of)

http://www.msm.cam.ac.uk

Materials Science is an interdisciplinary subject incorporating elements of physics, chemistry, engineering and increasingly even biology. Generally material scientists are interested in two key questions: firstly, why does a material behave the way it does and secondly how can we exploit or change the properties of a material to make it better or cheaper? Our society is highly dependent on advanced materials. These can range from lightweight composites for transport, silicon microchips for computing, complex materials and structures for renewable and efficient energy supply, and materials to support our ageing population. Materials science can be investigated across a variety of length scales and structures right down to the atomic scale - affecting the gross properties of materials.

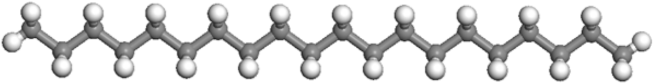
Polymers are more than just plastic bags, packaging or toys. They can be designed to dissolve in water, conduct electricity, or change colour or shape with the application of an electric field or heat. Polymers have always been around; natural polymers include the proteins that make up all living things, cellulose, starches, wood, silk, wool and natural rubber. It wasn't until the early 19th Century that the first processed polymers were used. In fact, most synthetic polymers were discovered by accident! The introduction of processed natural rubber and the use of crude oil as a new source of organic compounds kick-started the idea that polymers could be developed for specific purposes with specific properties.

In current times, polymers are used in a huge variety of applications because of their wide range of properties.

What is a polymer?

Polymers are long molecules consisting of chains or networks of many repeating units. They are formed by chemically bonding together many small molecules called monomers. Polyethylene is perhaps the simplest synthetic polymer and has a structure demonstrated in *Figure 1.* It is what is known as a hydrocarbon with only carbon and hydrogen atoms attached to a carbon backbone. Polyethylene is found in everything from carrier bags, to medical implants, to water pipes (*Figure 2)*.

Polymer chains may have a single backbone (which is likely to contain many kinks) or they may be branched. It is also possible for some polymer chains to have bonds between them known as cross-links. These cross-links affect the properties of the polymers as they prevent the chains from being able to move past each other. A simple experiment to demonstrate this is the formation of a cross-linked polymer using PVA glue and borax. Borate ions in the borax form cross-links with the polymer chains in the PVA glue and make what was initially a viscous liquid turn into a gel (*Figure 3*). However, these cross-links are relatively weak and give the material what is called non-Newtonian behaviour. If the polymer is pulled slowly, the bonds are temporarily broken and chains are able to slide over one another, before bonds are reformed. However, if pulled quickly cross links cannot reform and the polymer snaps!



🡅 ***Figure 1:*** *Linear chain of poly(ethylene). The monomer unit is CH_2=CH_2. Image courtesy of DoIT PoMS, Department of Materials Science and Metallurgy, University of Cambridge.*

🡅 ***Figure 3:*** *PVA glue, otherwise known as*

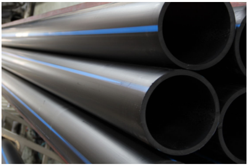


Figure 2: *Polyurethane has a vast array of applications.*

poly(vinyl alcohol), with borax added to form cross-links. Here, the polymer has been allowed to stretch slowly under its own weight.

↑ ***Figure 4:*** *A shattered polymer squash ball – cooling to -196°C resulted in the rubber ball becoming brittle*

Temperature can also have an impact on whether a polymer is brittle (will snap easily) or plastic (can be deformed without breaking). Vacuum forming is a common route for the production of simple plastic objects such as cups and yoghurt pots. When heat is applied to some polymers the molecules gain enough energy to move apart, slide over each other and become untangled. This means they can become soft when heated and formed into all sorts of shapes. Below a certain temperature, known as the glass transition temperature, the polymer chains can no longer slide past each other and they become 'frozen' together (*Figure 4)*.

Name: Dr Jennifer Shepherd

Position: Postdoctoral Researcher

Company: Department of Materials Science and Metallurgy, University of Cambridge

Educated in: Coombeshead College, Newton Abbot

A-levels (or equivalent): Maths, Physics, Chemistry, History (AS Further Maths)

University: University of Oxford, University of Cambridge

Qualifications: MEng Materials Science, PhD Materials Science

My day to day work involves... trying to mimic the materials and structures within the body to better treat injury and disease. Currently my work focuses on the natural polymer collagen, trying to produce and characterise 3 dimensional structures to allow tissue regeneration for applications such as heart repair. The work is extremely varied using chemistry to optimise the materials, physics to image and characterise the structures and biology in order to investigate how human cells respond.

Other experience or previous professions: industrial R&D in a small biomaterials company

The best things about my job are...working in a field where there is the potential to seriously improve the quality of people's lives; travelling to exciting countries to talk to scientists from all over the world, having very expensive toys to play with.

The thing I like least about my job is... not being able to switch off from it.

Other careers considered: Medicine, teaching, industrial R&D.

9. Mathworks

MathWorks®
Accelerating the pace of engineering and science

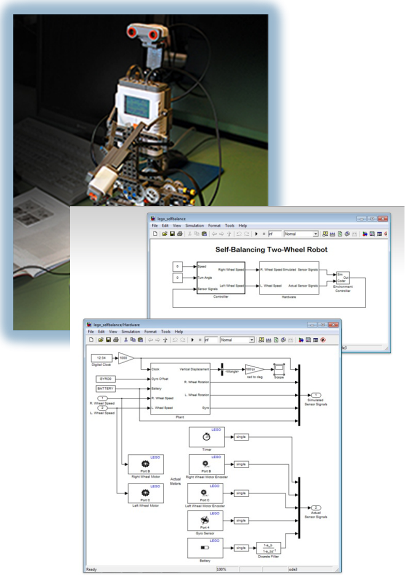
http://www.mathworks.co.uk

What does MathWorks do?

MathWorks is the leading developer of mathematical computing software. Engineers and scientists worldwide rely on its products to accelerate the pace of discovery, innovation, development and learning.

What are MATLAB® & Simulink®?

Physicists, scientists and engineers use computers to analyse data from their experiments, visualise them and discover patterns and new characteristics in them. MATLAB is the leading environment for performing such scientific and technical computing. They also use graphical tools to build computer models to simulate the behaviour of real world systems. Simulink is a graphical environment for simulation and Model-Based Design.



MATLAB and Simulink enable fundamental research, the design and development of a wide range of advanced products, including automotive systems, aerospace flight control and avionics, telecommunications and other electronics equipment, industrial machinery, and medical devices. More than 5000 colleges and universities around the world use MATLAB and Simulink for teaching and research in a broad range of technical disciplines.

Hardware support for Project Based Learning

Project-based learning allows students to obtain 'hands-on' learning techniques and gives students direct exposure to hardware and software. By incorporating industry-standard software tools such as MATLAB and Simulink, teachers can introduce students to the exciting field of technical design and innovation. Furthermore the students also develop a whole host of skills highly sought by employers in a wide variety of careers. MATLAB and Simulink allow for such project-based learning through built-in support for interfacing with low-cost hardware, including Arduino®, LEGO® MINDSTORMS® NXT, and Raspberry Pi® platforms.

The Experiment

Physics provides us with the tools to model 'real-world' physical systems. Specifically this means we can represent a real system through a mathematical model of its component parts. Such models allow us to simulate the system in a variety of different scenarios without actually having to build any of the hardware involved. This has the advantage that different solutions can be tested *virtually* saving both time and money by uncovering design flaws and allowing the design to be optimised before actual implementation.

The demonstration will introduce physical modelling and computer simulation in order to control a two-wheeled segway robot using Simulink and a Lego Mindstorms NXT.

Name: Dr Gareth Griffiths

Position: Quality Engineer

Educated in: Elfed High School

A-levels (or equivalent): Maths, Physics, Chemistry

University: University of York, University of Cambridge

Qualifications: MPhys Physics with Astrophysics (York), PhD in Computational Physics (Cambridge)

My day to day work involves... working closely with software developers to ensure that the code they write is thoroughly tested; for correctness, performance, and compatibility.

The best thing about my job is... the combination of teamwork and individual creativity required and the interesting people that I work with

The thing I like least about my job is... Not having enough time to work on the most exciting projects all the time- and the deadlines!

Other careers considered: Pilot, Finance (was a physics teacher)

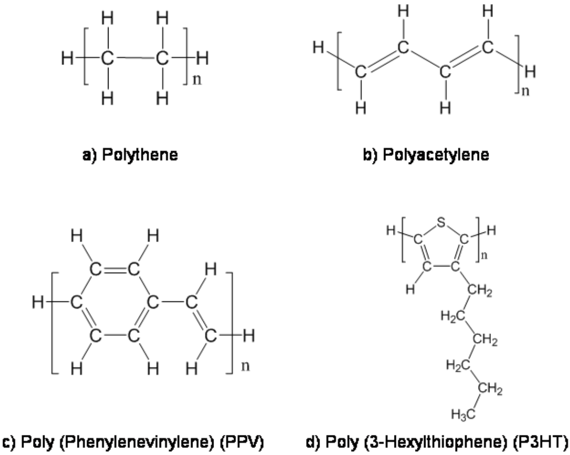
Cavendish Laboratory

10. Optoelectronics Research Group

http://www.oe.phy.cam.ac.uk

Conduction in Polymers

Look around you and you will find a diverse range of things, from cling film to artificial limbs, made from plastics. Plastics themselves are made from long chain organic molecules consisting mainly of hydrogen and carbon arranged in different ways (figure. 1). Most of these well-known plastics are insulators and can be used as a shielding on electric cables to protect you from electric shock.



a) Polythene

b) Polyacetylene

c) Poly (Phenylenevinylene) (PPV)

d) Poly (3-Hexylthiophene) (P3HT)

↑ ***Figure 1:*** *Polythene is used in plastic bags whereas PPV is commonly used in organic LEDs and P3HT is used in organic transistors.*

A newly discovered group of polymers have electrical properties similar to silicon, which is a semiconductor. The polymer chains have alternating double and single carbon bonds (figures. 1b, 1c and 1d) and the materials made from them can conduct electricity under certain controllable conditions. Research in the Optoelectronics Group is based on trying to understand how these polymers conduct electricity and how they can be used as LEDs (light emitting diodes), photovoltaics (solar cells) and transistors.

Light Emitting Diodes (LEDs)

LEDs are extremely common and are used as tiny, low current lamps; for example as the ‘on’ indicator on electrical appliances. They emit light by a process in which electrical energy is transferred into light energy without any heating effect, unlike the case of a tungsten filament lamp. Most LEDs are made from inorganic silicon-like materials.

However, polymer LEDs are easier to make than conventional LEDs. They have all the advantages associated with plastics, particularly cheapness. An example of a light-emitting polymer is PPV (shown in figure. 1c). Polymer LEDs can be made to emit red, green and blue light, which leads naturally to making full colour flat-screen TVs (figure 2) and back lit displays for mobile phones.

Photovoltaics

Solar cells are found in solar powered calculators, clocks and satellites, where the energy from the sun is used to generate electricity. In an LED, electrical energy is transferred into light energy. By running an LED ‘backwards’ the light energy can be transferred into electrical energy in a solar cell. Light absorbed by the polymer generates positive and negative charges that can be collected at electrodes and the solar cell will then act like a battery. The problem is that positive and negative charges like to stick together, but they can be pulled apart by making the solar cell from two different polymers, one of which attracts negative charges and the other

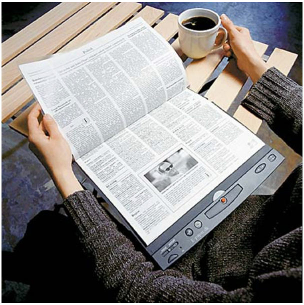
↑ ***Figure 2:*** *A huge (40”) plastic TV screen*

🡅 ***Figure 3:*** *Flexible solar cell battery used to power electronic equipment (image taken from http://www.rangermade.us/store/catalog/images/solar.JPG)*

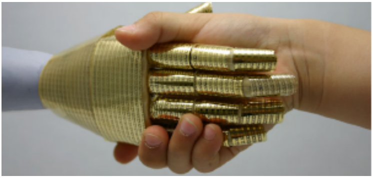
positive charges. Conventional solar cells are made from silicon, which is costly to process, but polymer solar cells can be produced very cheaply and large arrays will be able to bend flexibly around objects or roll up for ease of transportation (figure 3).

Field-effect transistors (FETs)

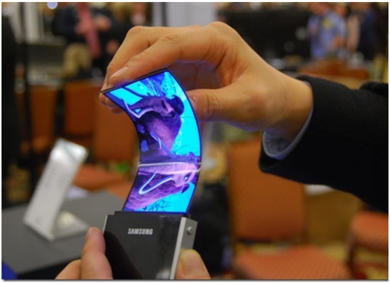
An FET is an electronic switch. When a voltage is applied to one terminal to form a path for charge, it is 'ON' and charges can flow between two other terminals. When the voltage is removed, the path disappears and it is 'OFF'. The FET is the basis of all modern microchips and a modern computer has several million FETs processing the information. Using polymer FETs, flexible microchips can be produced at very low cost so it has big advantages in high volume applications. Recently, the best polymer FETs showed similar speed to FETs made of amorphous silicon and there is a strong possibility to develop new polymers with better performance. Moreover, due to a polymer's intrinsic flexibility and light weight, it can be applied to new products such as electronic newspapers (figure 4) or "smart skin" covering artificial limbs (figure 5).



↑ ***Figure 4:*** *A flexible electronic newspaper*



↑ ***Figure 5****: Artificial skin which senses cold/hot or feels the handshake*



↑ ***Figure 6:*** *Samsung's flexible screen*

Watch out for polymer electronics coming out. OLED screens are already in use in some mobile phones and flexible screens are expected to be on the market within the year. Maybe one day we will be able to watch TV on a polymer screen and then roll it up like a poster when the programme is finished! Plastics have a very exciting future.

Other useful websites

Cambridge Display Technologies:
http://www.cdtltd.co.uk

Plastic Logic:
http://www.plasticlogic.com/

Readius: http://www.readius.com

Name: Aditya Sadhanala

Position: PhD student in hybrid-polymer photovoltaics

Educated in: Mumbai, India

A-levels (or equivalent): International Baccalaureate equivalent with pure Maths, Physics, Biology and Chemistry

University: Manchester, UK and Mumbai, India

Qualifications: Bachelor of Electronics Engineering, Msc in Nanoelectronics

My day to day work involves... analyzing results from my experiments where I made polymer samples on glass and test them under a special machine built by me, which measures the amount of light absorbed by the polymer material. The interesting thing here is that this machine is inspired by the natural mirage effect which gives you an illusionary effect when observing distant objects!

The best thing about my job is... making new things in the lab, gaining knowledge and helping out other people in the group

The thing I like least about my job is... it can get a bit busy at times!

Other careers considered: Inventor, engineer, farmer and cricketer.

Name: Monika Szumilo

Position: PhD student (2nd year)

Educated in: University of Manchester (BSc Hons in Physics with Techological Physics), University of Cambridge

A-levels (or equivalent): Physics, Maths, English

My day to day work involves... preparing and measuring devices with semiconducting polymers. I prepare samples in a laboratory and analyse data on my computer using a self-written software. Most of the samples are prepared in a clean room/a very clean environment with filtered air or in glove boxes filled with nitrogen so when working there I need to wear a special suit that prevent my samples from contamination.

Other experience/previous profession: My MPhil course was research-based so my PhD is a form of a continuation. I also teach first and second year undergraduate students.

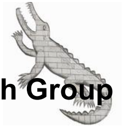
The best thing about my job is... it’s cutting edge research so it’s fascinating so I can learn a lot!

The thing I like least about my job is... I sometimes need to work with dangerous chemicals so I need to be careful and focus

Other careers considered: Musician, teacher

Cavendish Laboratory

11. Theory of Condensed Matter Research Group



http://www.tcm.phy.cam.ac.uk

Theoretical Physics

Scientists try to understand the world around us - both immediately around us, and at the extremes of distance, energy and time. Modern science would have got nowhere without careful, and often surprising, experimental observations.

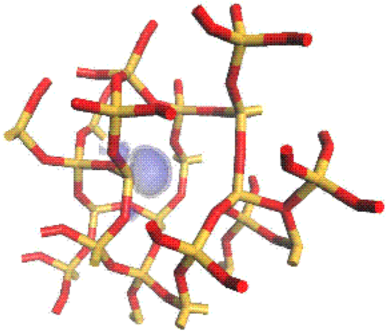
But all scientists are theorists as well, as they seek to understand their experimental results, developing the simplest possible theory that explains all the known facts.

The best theories not only elegantly summarise what is known already, they allow predictions to be made about things that have never been seen before. So, in addition to building theories, theorists explore their consequences. This might be done to test how well the theory works in extreme or unusual circumstances, or to discover new phenomena.

Mathematics is the language of theory, certainly in the physical sciences, and increasingly in biology. It is not just a descriptive language - it is a tool that allows the theories to be manipulated, improved, or even disproved. Equations are solved - known quantities are used to discover the unknowns. With the advent of modern powerful computers theorists have gained a new tool. Not only can computers now do many mathematical tasks, such as solving very complex equations, they can also manipulate theories that would be very difficult or impossible for a traditional mathematician to handle using a pencil and lots of paper.

The Theory of Condensed Matter (TCM) Group at the Cavendish Laboratory is a group of theorists who are interested in understanding "condensed matter". Most of the "stuff" in the universe that we, as humans, are likely to be able to touch is condensed matter. This includes semiconductor crystals and liquid crystals, metals and superconductors, minerals that might be found deep in the Earth or other planets, and even molecules that keep us alive. The fundamental theory that our research relies on is called "Quantum Mechanics", and was developed in the early 20th century. Quantum Mechanics describes the mechanics of the very small particles that most matter is made of: electrons, protons and neutrons. The equations that we still believe explain most of the phenomena that we can see around us were written down over fifty years ago, but were impossible to solve!

In the TCM Group, using theoretical advances and enthusiastically making use of computers and supercomputers, we are actually solving these equations for a vast range of realistic situations, from discovering what makes diamond so strong, to understanding proteins. We have developed two state-of-the-art computer programs: CASINO and CASTEP. CASINO allows the very accurate simulation of Quantum Mechanics, but it takes a lot of computing power. CASTEP on the other hand is less accurate, but good enough for many purposes: it can be used to calculate the properties of very large collections of atoms. CASTEP was originally purely an academic computer program, used exclusively by researchers in universities. It was later licensed by Cambridge Enterprise, the University's commercialisation arm, to Cambridge-based software company Accelrys in 1995 and is now marketed commercially by the company. Accelrys are a scientific software company whose European headquarters is based in Cambridge on the Science Park. They now have several hundred commercial customers who are actively using theory to solve industrial problems. The total sales of CASTEP have recently passed $30 million.



↑ ***Figure 1:*** *An electron sitting on a defect in glass (SiO_2). The "blob" near the centre indicates the position of the electron. The "tubes" represent the bonds between the silicon and oxygen atoms in the glass. Experimental measurements of the behaviour of the trapped electron in a magnetic field allow a lot to be said about the arrangement of the atoms around the defect. Theoretical predictions help this interpretation.*

12. British Antarctic Survey (BAS)

http://www.antarctica.ac.uk

Ozone Measurements in the Antarctic

http://www.antarctica.ac.uk/met/jds/ozone

Ozone is a gas consisting of three oxygen atoms and it is formed by the action of sunlight on normal oxygen. When ozone is found near the surface of the earth (such as in smogs formed from car exhausts) it is a noxious substance. Much higher in the atmosphere, the ozone layer protects us from the harmful effects of ultra-violet radiation.

BAS scientists discovered the Antarctic ozone hole over twenty-five years ago and continue to study its annual formation and disappearance. The "Hole" varies in size and duration from year to year, depending on the "weather" in the upper atmosphere. The 2014 hole will be nearing its deepest as Physics at Work takes place - what will we see? Some ozone depletion is seen over the Arctic during the spring, and whilst it can be severe, as it was this year, no major ozone hole has so far formed there. The physics behind the instrument that measures ozone will be explained and you will discover why it is normally only the Antarctic ozone layer that develops a large hole each spring.

Although the amount of ozone depleting gasses in the atmosphere is now declining, we think that it will be another decade before we can say for sure that the ozone layer is beginning to recover.

Some topics to think about before coming to the exhibition:

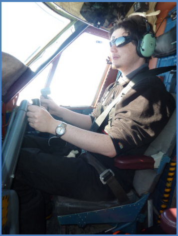
1. Differences between the Antarctic and Arctic.

2. Many environmental changes will take place over tens of years, but the measuring instruments may only operate over a few years. How can we tell if or when there has been a significant change in what we are measuring?

🡅 ***Figure 1:*** *BAS scientist Jon Shanklin makes an ozone measurement at Halley station.*

🡅 ***Figure 2:*** *Emperor penguins on the sea ice not far from Halley station.*

🡅 ***Figure 3:*** *The aurora australis (southern lights) above Halley station.*



Name: Tim Barnes

Position: Data Manager

Educated at: Hills Road Sixth Form College, Cambridge

A-levels (or equivalent): Maths, Physics, General Studies, Further Maths (AS-level)

University: University of Reading, Anglia Ruskin University

Qualifications: BSc (hons) Physics and Meteorology, PGDip Computer Science

My day to day work involves... ensuring that data is transferred from the Antarctic stations to our HQ in Cambridge, and then making data available to the scientists and their collaborators. Additionally, I set up computer systems for installation on the stations, as well as monitor them remotely from the UK.

The best thing about my job is... Trips to the Antarctic.

The thing I like least about my job is... Paperwork.

Other careers considered: Meteorologist

13. Domino. Do more.

http://www.domino-printing.com

What does Domino do?

Domino use a printing process called continuous ink-jet printing to mark and label a vast range of products, varying from the eggs you eat for breakfast, to the numbers printed on your winning scratch card. Virtually everything manufactured today had been coded, labelled or marked before reaching you – the consumer.

The history of Domino...

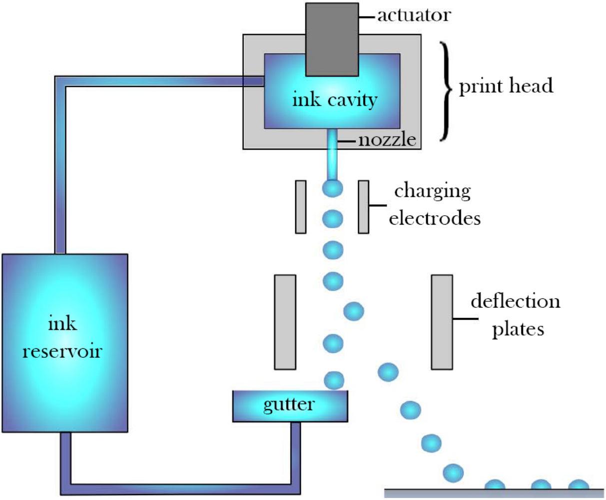
Domino was founded in Cambridge in 1978. Not long afterwards EU legislation was introduced requiring all food products to be marked with a best before date. Continuous ink-jet printing provided a perfect solution, as it is fast and doesn't involve contact between the printer and the product.

So what is continuous ink-jet printing?

Continuous ink-jet printing involves the jetting of ink onto a surface without being in contact with it. The main advantage of continuous ink-jet printing is the speed: a single nozzle can generate up to 150,000 drops per second, which allows the surface being printed to travel over 10 mph (up to 5 m/s).

Continuous inkjet printing is different to the drop on demand ink-jet printing used in your desktop printer. Drop on demand printing has hundreds or thousands of nozzles in a line, which each print a single drop when the nozzle is triggered. However the continuous ink-jet printing used by Domino only uses a single nozzle, which is continuously forming drops. Ink is constantly being jetted through a nozzle, which is about the same width as a human hair.

If you squirt water through a hosepipe the jet will eventually break-up into drops; this is because the jet becomes unstable due to natural pressure fluctuations. A similar technique is used in continuous ink-jet printing; by introducing a controlled vibration within the jet, the stream of ink can be made to break-up into regularly sized drops.



↑ ***Figure 1:*** *A simple example of a continuous ink-jet print system*

Figure 1 shows the basics of how a continuous inkjet printer works. Ink in the ink cavity is jetted through the nozzle. A vibration is introduced by an actuator behind the nozzle - this makes the jet break into drops. The drops then pass through a charging electrode, which causes the drops to become charged as they pass through it. The charged drops then pass through deflection plates. One is held at a negative voltage and one is kept positive, creating an electric field between the two plates.

As a charged drop passes through the electric field it is attracted to the deflection plate with the opposite charge, and repelled by the plate with the same charge. The electrostatic force causes the drop to change direction as it passes through the deflection plates. The change in direction is used to steer the drops onto the surface of the product being printed.

If a drop doesn't need to be printed the charging electrode does not charge the drop, so it is not deflected and travels straight down and lands in the gutter. The unused drops are then recycled and printed again. In order to get a complex pattern the charging electrode charges some drops more than others. Drops with more charge will deflect further so a larger area can be printed.

And the future?

Domino does not just print on products, they also print the boxes the products are put in, and even on the pallets the boxes are loaded on.

Domino does not only sell continuous ink-jet printers, but has a range of products including full colour drop-on-demand label printers, laser scribing and thermal transfer printers.

So next time you go to the supermarket, have a look at how many items have probably been printed using a Domino print-head!

Cavendish Laboratory

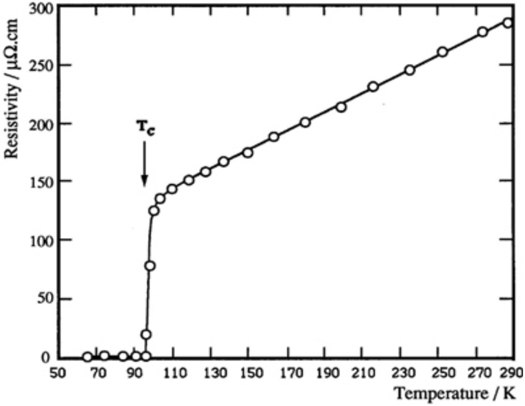
14. Quantum Matter Group

http://www-qm.phy.cam.ac.uk

What is superconductivity?

In 1911, at Leiden University in the Netherlands, Professor Onnes was cooling down mercury with the newly discovered cryogen, liquid helium, and measuring its resistance. When the temperature reached 4.15 K [-269 °C] the electrical resistance suddenly dropped to zero. After a lot of checking, this result was found to be correct, and the effect was called superconductivity. Many other superconducting materials were discovered over the next 75 years but none of them was found to be superconducting above 23 K [-250 °C].

Discoveries made in the past 25 years have raised superconducting transition temperatures to a much higher value. Scientists at the University of Houston first synthesised a ceramic compound containing yttrium, barium, copper and oxygen, which becomes superconducting at 93 K [-180 °C]. Its chemical formula is $YBa_2Cu_3O_7$ although the material sometimes loses oxygen.



↑ ***Figure 1:*** *The variation in resistivity of $YBa_2Cu_3O_7$ with temperature.*

Figure 1 shows the sudden disappearance of the resistivity of $YBa_2Cu_3O_7$ on cooling the sample. Other ceramic compounds containing copper also give high transition temperatures. The cuprate superconductor with the highest transition temperature is $HgBa_2Ca_2Cu_3O_{8+d}$, which shows superconductivity at 160 K [-110 °C] under pressure.

↑ ***Figure 2:*** *A $YBa_2Cu_3O_7$ superconducting disc being "levitated" by a permanent magnet.*

These newer ceramic superconductors are known as High Temperature Superconductors, and are superconducting in liquid nitrogen, which is much cheaper than liquid helium - however being ceramics, like a teacup, they are brittle.

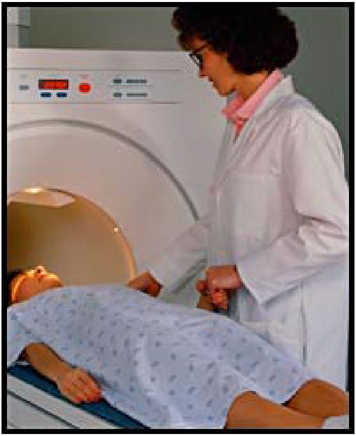
Why is superconductivity important?

If you pass a current along a normal copper wire, energy will be lost because the wire has a resistance. If the wire is a power cable this loss is significant. In fact 1.5% of the power generated in the UK is lost in transmission. This is significant but the real problem is that if you do not want your wires to melt you have to dissipate this heat. Superconductors do not have any resistance so there is no heat to dissipate; this means that you can put much more current in the same space. This property of superconductors can be exploited to increase the capacity of cables in the centre of a city, without having to dig up the road.

To make a strong electromagnet you also need a very large current in a small space, therefore, superconductors are very suitable for making electromagnets. Superconductors also have the advantage that once you have a current, they do not use any power. However, superconductors do have disadvantages. You have to cool them down to between –200°C and –269°C, and the high temperature superconductors are brittle ceramics, which means making wires from them is challenging.

Superconducting magnets are used in MRI scanners, mineral separation machines, and recently in high power compact electric motors for powering large ships.

Superconductors interact with magnetic fields in interesting ways, which allows them to be used to make very sensitive magnetic sensors, and high frequency microwave and terahertz receivers. They can also be used for very high frequency electronics and possibly for quantum computing.



↑ ***Figure 3:*** *A Magnetic Resonance Imaging machine (MRI)*

Promising applications of High Temperature Superconductors:

Superconducting component	Benefit	Market/Application
Resonators, filters, delay lines	Well controlled, high frequency circuits	Communications
Magnets, cables, windings	High current density	Use of electrical energy
Scientific/medical instruments	Sensitive control and creation of magnetic fields	Study of materials, geology and medical patient imaging.

15. Rolls-Royce

http://www.rolls-royce.com

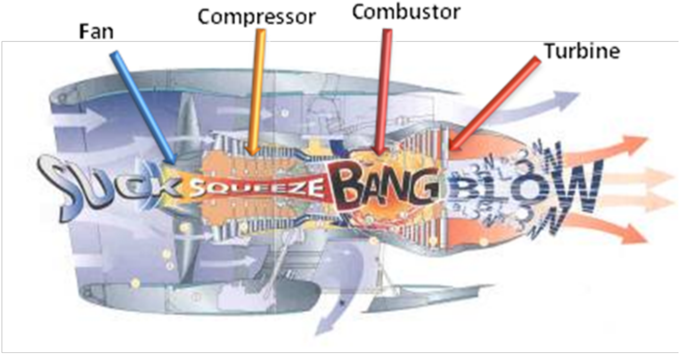
What does Rolls-Royce do?

Rolls-Royce is a global power systems provider, supplying our products across civil aerospace, defence aerospace, marine and energy. Our organisation is steeped in heritage, particularly in the car industry, but these days our products focus on much larger, more complex applications:

- Jet engines for civil aircraft, military aircraft and helicopters
- Gas turbine engines for ships and power stations
- Nuclear power for the energy industry and submarines

The Gas Turbine

Gas Turbines are a type of engine but have a very different architecture to those found under the bonnet of a car. There is a continuous flow of air through the engine that goes through four phases to produce power:



Intake and Fan (Suck): A 3 metre diameter fan spinning at 2500 rpm draws in huge quantities of air per second

Compressor (Squeeze): Compressors accelerate and squash the air until it is 40 times smaller than its original size

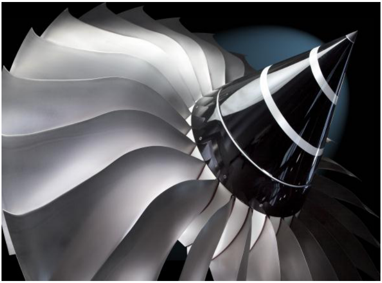
Combustor (Bang): Fuel is injected into the combustor and the air/fuel mixture ignited. Temperatures here can reach up to 1750 °C
Turbine: Some of the kinetic energy from the hot fast gas is extracted to spin the turbine, which in turn drives the compressors

Exhaust: The air is propelled backwards out of the rear of the engine. Newton's Third Law says that "Every action has an equal and opposite reaction" – the hot gases rushing out of the rear of the engine result in an equal and opposite forwards thrust force

How to Generate Power

Highly advanced materials are required to push the boundaries of power generation within a gas turbine. Rolls-Royce pioneers many of these technologies and manufacturing processes to ensure our products are the best. You'll see these technologies at our exhibition.

- Fan Blade Technology



Fan blades experience high levels of stress due to their elongated shape, meaning the material wants to pull itself apart. The fan must also be extremely light to provide maximum compression power with minimal effort.

They are manufactured hollow using a 'web' to strengthen the material

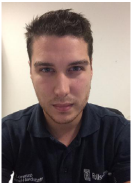
- Turbine Blade Technology

Turbines blades extract power from the hot fast gases downstream of the combustor. Each one, in fact, can produce around 750hp – the same as a Formula1 car! They spin at around 12,500 rpm and live in an environment 200°C hotter than their melting temperature. That's like putting an ice cube inside an oven.

To cope, they must be light and strong (achieved by using a high-strength material and advanced 'single crystal' casting methods) and must contain complex cooling mechanisms where cold air is blown through the blade to form a protective coat.

Name: Lorenzo Kirkland-Hardstaff

Position: Advanced Technical Apprentice



Educated in: Landau Forte College (GSCE & A-Level), Derby College (HNC)

A-levels (or equivalent): Engineering (double), AS Maths, HNC Manufacturing Engineering

University: Sheffield Hallam – Through Rolls-Royce

Qualifications: Studying Foundation Degree in integrated engineering (Mechanical) leading to BEng in Mechanical Engineering.

My day to day work involves... four days of the week I work at the Rolls-Royce Rotatives plant in Derby as a manufacturing engineer. I am currently placed in the discs quality division, where we explore reasons for products not meeting their design specification. Once a week I attend my university course, sponsored by Rolls-Royce.

The best thing about my job is... the involvement in real engineering situations whilst still in education. This allows for a greater understanding of the practical application of the theory I've been taught.

Other careers considered: RAF Pilot.

Name: Nathan Turner

Position: Engineering graduate.

Educated in: University of Oxford, Sir Harry Smith Community College (Peterborough).

A-levels (or equivalent): A2's Maths, Further Maths, Physics, Chemistry, Biology.

University: University of Oxford.

Qualifications: MMath Mathematics (Four year mathematics course).

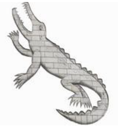
My day to day work involves... I get to choose a variety of placements. So far I have investigated cost savings associated with services, created a new tool to calculate turbine efficiency and worked in the Whole Engine Design Team for a future demonstrator programme. Currently I work in the Performance Team where we use computer simulations to predict performance of engines on test.

The best thing about my job is... I get to work with lots of different people in the business – from the senior project managers to the guys building the engines on the shop floor. I also get to develop what I learned in my degree which was very theoretical – by applying my skills to tackling real world problems. The people and the hours are great, meaning I can have a good work-life balance

Other careers considered: PhD in engineering, University Tutor/Lecturer, Data Scientist, Formula1 aerodynamicist.

Cavendish Laboratory

16. Fracture and Shock Physics Group



http://www-smf.phy.cam.ac.uk

The Fracture and Shock Physics Group

The Fracture and Shock Physics Group is part of a larger group that was originally called the “Physics and Chemistry of Solids.” For over 60 years, these names have provided a good description of our work:

- *Physical phenomena:* How do materials age? What properties affect their strength?
- *Chemical phenomena:* Explosives and pyrotechnics
- *How materials break and fail:* How do different materials fail? How do they behave in impacts?

We have a world-wide reputation for studying the dynamic mechanical properties of materials. Today, we will show you some of the techniques we use and have developed to study the properties of materials in extreme conditions.

Our aims

We believe that the best way to increase our knowledge of the properties of materials is through a combination of experimental work and computer simulations and models. Our experiments are used in two ways:

- Simple experiments to help develop new models;
- More complex experiments to test the predictions of existing models;

We actively participate in industrial and academic research, and our work takes us all over the world.

Stress and strain

We can describe the effect a force has on an object in two ways: stress – the average force felt by the object – and strain – how much that force changes the size of the object. But when a force acts on a material, it isn’t just the size of the force that’s important, but the speed with which it’s applied: we call this phenomenon ‘rate dependency.’ A traditional example of this is silly putty: pull it slowly, and it stretches out to a thin fibre; pull it quickly and it snaps. When left for days it can even drip and flow through holes.

In reality, it means that the way a material behaves when deformed slowly can differ greatly from its behaviour at a fast rate of deformation. Within our group, we have equipment that can deform materials at rates from a few millimetres per hour to thousands of metres per second and every rate in between!

Stress concentration: flaws and failure

Materials fail when the stress in them exceeds their strength: usually this occurs because the stress has been ‘localised’ in one area by a flaw in the material. In part, the strength of a material depends on how a force is applied to it.

Understanding how stress builds up in a material – be it a single sheet of paper or an entire bridge – is vital if we want to predict how it will behave in everyday life. Today, we’ll look at ways we can see stress in materials, and how flawless materials can be surprisingly strong.

Energetic phenomena

The rate at which energy is delivered into an object has a dramatic effect on its behaviour. What if instead of slowly applying current to a light bulb, we put all the energy through the filament in a few nanoseconds?

Explosives generate a lot of gas and heat, and this can be used to do work. For example, a cannon uses the gas produced by burning gunpowder to force the cannon ball up the bore. Gunpowder on its own doesn’t do anything spectacular – its power comes when it is confined. We will demonstrate this by first burning gunpowder on the desk and then confined in a can by a cork. Strictly speaking, gunpowder is a propellant, not an explosive. The velocity at which a burning reaction moves in a propellant is typically around 800 m/s. Explosives detonate: The reaction moves through an explosive at thousands of metres per second. The fastest reaction you’ll see today is the explosion of a length of shock tubing – an explosive-filled plastic tube used to set off large explosions in quarries and mines.

High-speed photography

All these processes, like the failure of a material or detonation of an explosive, happen much faster than the eye can see. A normal television camera shows still pictures at the rate of 25 frames per second – our brain 'blurs' these images together to create the illusion of motion. In the laboratory, we employ cameras that can capture between 1000 and 100,000,000 frames per second to record ultra-fast phenomena. The first use of high-speed photography was to settle a bet: does a galloping horse ever have all four of its feet off the ground?

Today, we will use our high-speed video camera to show some of the surprising things that happen faster than the eye can see.

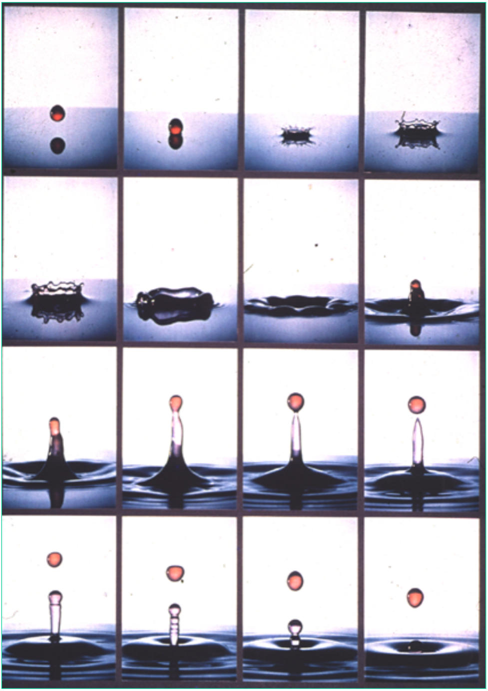
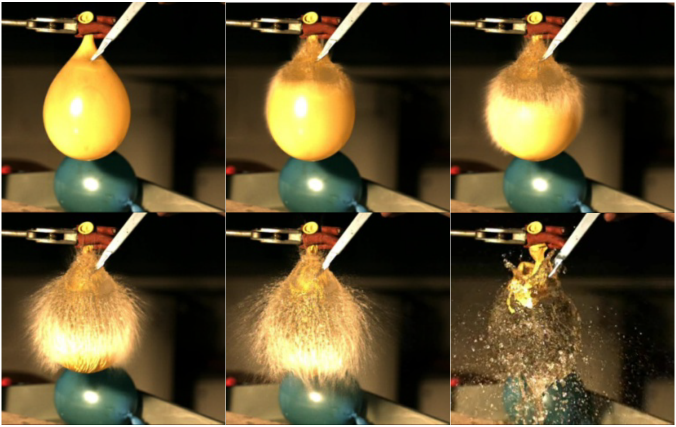
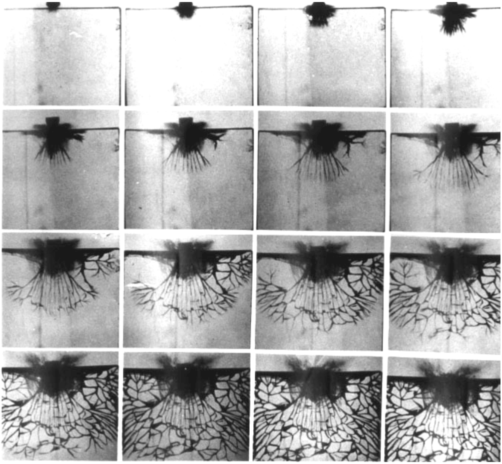


Figure 1: ➔
A sequence showing a drop of red-dyed water falling into a pool of blue-dyed water. In the first frame the drop nears the surface. In the second, the impact has occurred and the drop has pushed the liquid aside producing a crown-shaped splash. In the following frames, the liquid rebounds and throws up a column or jet. Sitting on top of the column is the original drop of coloured water.



🡅 **Figure 2:** *A sequence of images from a high-speed video recording of a water balloon being burst. Notice how the skin of the balloon 'unwraps' leaving a ball of water that subsequently falls away.*

Figure 3: 🡆
The propagation of cracks in a 50 x 50 x 6.2mm sheet of toughened windscreen glass after impact with a lead airgun pellet at the top. The time between frames is two millionths of a second.



Name: Simon Kirk

Position: PhD Student

Educated in: Shiplake College, Oxfordshire

A-levels (or equivalent): Maths, Further Maths, Physics, Chemistry

University: Peterhouse, Cambridge

Qualifications: BA hons, MEng in Mechanical Engineering

My day to day work involves... using a gas-gun to fire projectiles at rock samples at up to 1 km/s. The impact puts the sample under very high stresses and I use high speed sensors to measure what happens. I also use a CT scanner, like the ones in hospitals, to look at the 3-D structure in rock. During term time I teach undergraduate students in physics and engineering.

Other experience or previous professions: Design Engineer

The best thing about my job is... doing big experiments.

The thing I like least about my job is... when equipment breaks.

Other careers considered: Nuclear Engineering, Automotive Engineering

Name: Rachael Boddy

Position: Research student in SMF group

Educated in: Anthony Gell school in Wirksworth, Derbyshire

A-levels (or equivalent): Maths, Physics, Biology

University: Newnham college, Cambridge and Hughes Hall, Cambridge

Qualifications: BA hons, MSci in Physics

My day to day work involves... Performing experiments and analysing data.

Other experience or previous professions: Day chemist

The best thing about my job is… Opportunity to design and carry out experiments in areas which interest me

The thing I like least about my job is... Having to share time on equipment

Other careers considered: Royal Navy, Nuclear engineering

Cavendish Laboratory

17. Biological and Soft Systems Research Sector

http://www.bss.phy.cam.ac.uk

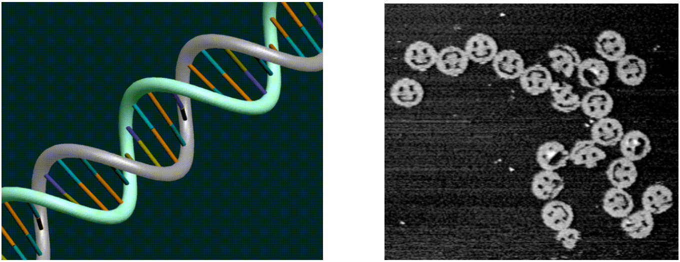
What is Biological Physics?

Traditionally physics and biology are considered to be two different subjects. Physics stands for the study of Newtonian mechanics, optics, electricity and magnetism, or simply the mathematical description of the motion and action of macroscopic objects. Biology on the other hand is the science describing how life is build up of complex molecules such as DNA or proteins that make part of the cells constituting our body. However, many famous physicists who are known for their achievements in 'hard condensed matter' and nuclear physics (like Erwin Schrödinger or Niels Bohr), and also natural scientists such as Darwin have contributed profoundly to our understanding of life. Some have done fundamental experimental work in areas such as molecular structure and dynamics, photosynthesis, or cell membranes. Others have applied their mathematical skills to develop theories for neural networks, electron transfer and phenomena such as the heart's rhythm. Others have found that their skill as instrumentalists can change medicine, through such advances as computed tomography and magnetic resonance imaging. All have experienced the excitement of working in this rich and interdisciplinary field.

DNA – a carrier of life and versatile building material for new applications.

The double helix of DNA was discovered here in the Cavendish by Watson and Crick. It is one of the greatest discoveries of the 20th century and led to the understanding we have of genes and how they work. But how are genes actually controlled? Is DNA always a double helix? And how does it all fit inside every human cell - there's 2 metres of it in every single cell?

But DNA can be used for much more than just biology - we can make new materials out of it, and make complicated three-dimensional shapes - a kind of DNA origami. We can use it to make tiny motors, and boxes that open and shut with a key. And maybe we can make computers out of it as well ... a true biological computer.

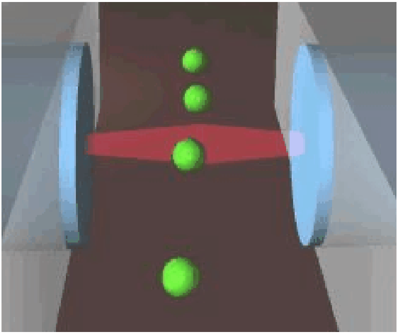


🡅 ***Figure 1:*** *DNA origami of viruses made by Paul W.K. Rothemund from a harmless virus-DNA. He "pinched" it into shape with "staples" made from much shorter DNA strands (ref.: P.W.K. Rohemund, Nature, Vol 440|16 March 2006|doi:10.1038/nature04586).*

Stretching cells with light: Early cancer diagnosis

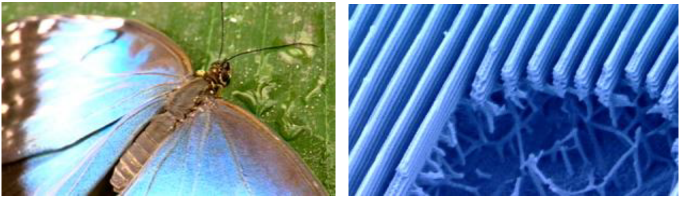
Just like mammals have a solid skeleton to keep the shape of the body and give it rigidity cells also have a skeleton – the cytoskeleton. This is made of specialized proteins that form long semi-flexible polymers giving cells their shape and mechanical strength. Physicists have found that when cells are exposed to two opposing laser beams a cell can be trapped by the optical pressure. This pressure can stretch the cell by varying amounts depending on its elasticity. In recent years researchers at the Cavendish have shown that cells of the same type become much softer (more deformable) when they are cancerous. Hence they developed a diagnostic tool from this to discriminate healthy from cancerous cells.

Figure 2: ➔ *Schematic of an optical stretcher. In a flow chamber, cells in suspension can be trapped by two opposing laser beams of low intensity, emanating from optical fibres. Increasing the intensity of the laser light augments the forces at the surface of the cell, leading to measurable deformation. Publication: J.Guck et al., Biophysical Journal 88:3689-3698 (2005)*



Butterfly wings: Colour produced by structure

Some colours we observe in Nature are not caused by pigments but simply by micron-sized building blocks that are arranged in a very ordered fashion. Examples are opals, which are semiprecious stones made of spherical silica particles. Some butterflies and beetles show coloured wings that are due to sub-micron structures and not pigments.



🡅 ***Figure 3:*** *The blue color of the wings of the Morpho (left) is due to the highly regular packing of its building blocks (right). (reference: Y. Zheng, X. Gao and L. Jiang, Soft Matter, 2007, DOI: 10.1039/b612667g)*

Researchers in the Biological and Soft Systems sector of the Cavendish Laboratory are learning from these examples in nature in order to make new ‘photonic’ materials that could be used to develop better light-harvesting solar cells, lasers, and mirrors for electronic applications.

18. Arcola Energy

http://www.arcolaenergy.com

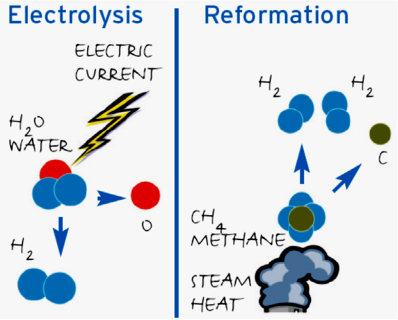
The "hydrogen economy" is a proposed system of delivering energy using hydrogen and fuel cells. The objective is to eliminate dependence on fossil fuels, using hydrogen as an energy carrier to combine a range of clean renewable energy generation technologies such as wind and solar power with clean power technologies such as fuel cells.

What is hydrogen and where do we get it?

Hydrogen is the most abundant element in the universe making up 75% of all matter by mass; however it doesn't occur naturally anywhere on earth – it is always contained in other compounds. For this reason it has to be produced and there are several different methods to do this including: reformation of natural gas, gasification of coal or biomass and electrolysis of water. The method used is very important in determining the environmental impact of a hydrogen economy as the amount of CO_2 emitted during the production of hydrogen can be very significant.

Examples

Steam Reformation: Reacting steam with methane gas (or another hydrocarbon) to separate hydrogen and carbon. The carbon is typically released as carbon dioxide and the hydrogen is captured for later use. This is not the cleanest method of hydrogen production as it releases substantial amounts of CO_2.



Electrolysis: Uses electricity to drive an electrochemical reaction to separate water into hydrogen and oxygen. In this case the electricity source is very important – using electricity from the grid will not directly reduce CO_2 emissions as grid electricity is primarily made by burning coal and gas; however electricity from renewable sources allows you to produce hydrogen in a clean way.

How can we store it?

Hydrogen storage is a key challenge in the development of a hydrogen economy. The great benefit of hydrogen is that it can be stored without degradation (unlike batteries), and be used whenever and wherever it is needed. However, since hydrogen is the smallest element, containing 1 proton and 1 electron, it can be tricky to store and some methods result in the loss of energy. Hydrogen stored as a gas has good energy density by weight, but poor energy density by volume versus hydrocarbons (such as petrol) hence it requires a larger tank to store. This is not a problem for stationary applications, however for portable power and vehicles this is an issue and vast research is taking place to solve this, using different options including nano-materials and chemical solutions such as metal hydrides.

Large, medium and small hydrogen storage and delivery

How can we use it?

Hydrogen is an energy carrier and not an energy source, meaning that it can be used to transfer energy, like electricity, but must be created from another primary energy source such as coal or wind energy. Hydrogen has been used for transport, power generation and heating. An advantage of hydrogen is that it can be used with a fuel cell to create electricity due to its electrochemical properties.

But what is a fuel cell? It is a device that converts the chemical energy of a fuel into electricity, similar to batteries. It consists of two electrodes and an electrolyte between them. Both electrodes (called the anode and the cathode) contain a catalyst that reacts with hydrogen and oxygen to create electricity. Fuel goes in the through the anode where a chemical reaction takes place splitting the proton from its electron. The proton travels through the electrolyte and the electron travels through an external circuit from the anode to the cathode, producing direct current (DC) electricity. The proton and electron rejoin at the cathode and combine with oxygen to produce a small amount of water and heat. This is the only by-product at the point of use. It is this characteristic that makes fuel cells ideal devices for the transition to a hydrogen economy and clean energy future.

A hydrogen fuel cell can be used for various applications such as stationary, portable and vehicle applications. This technology is already available and being used around the world.

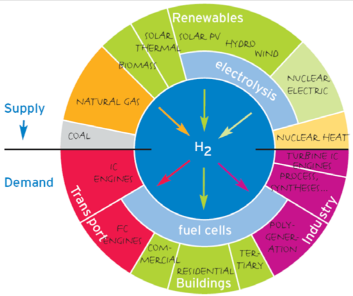
This sounds too good to be true! What's the catch?

There are issues facing the adoption of the hydrogen economy

Cost: At present costs are too high. Extensive research and development is underway to make all aspects of a hydrogen economy more cost effective.

Current technologies: A major barrier is that current technologies already work! Combustion of coal and oil is widely used and accepted. While this may be the case, it comes at a cost to the environment. These processes all create significant amounts of CO_2 and the resources are becoming less readily available.

Efficiency: Converting electricity to hydrogen and back again is much less efficient than using batteries. However there are many applications for which batteries are not suited, particularly at the larger-



scale. It is crucial to increasing our use of renewable energy that we find means of storing large amounts of energy.

Public acceptance: As with all the new technologies, there are barriers to overcome before hydrogen becomes accepted by the public. One of the biggest concerns amongst the public is the issue of safety. Hydrogen is highly flammable and if handled wrongly can be dangerous; however hydrogen has a very good safety record during decades of use in industrial applications.

Name: Mr Arlan Harris **Position:** Designer/Engineer

Educated in: Anglo European School, Ingatestone, Essex

A-levels (or equivalent): Maths, Chemistry, Biology, Philosophy, French

University: Camberwell College, UAL **Qualifications:** BA hons 3D Design

My day to day work involves... Designing and managing the Arcola Energy website and forum, writing brochures, press releases and manuals for new products, conducting lectures for school and university students, running workshops for school students, acceptance testing products and developing new fuel cell based products such as our Hydrogen/Electric bike.

Other experience or previous professions: Product design, sound engineer, audio equipment design, construction, landscaping, music production and DJ.

The best thing about my job is... Being at the forefront of fuel cell technology and development within the UK.

The thing I like least about my job is... Acceptance testing products before they are sent to customers.

Other careers considered: Sound engineer, product designer, and audio equipment designer.

Name: Amanda Rose Bicott

Position: Sales & Marketing / Work shop leader

Educated in: University City High School, San Diego, California, USA

My day to day work involves... Working closely with engineers to bring cutting edge low carbon technologies to market and answering technical questions from enquiries on our website. In addition to general sales and support I also deliver workshops to young people teaching them about renewable energy and hydrogen fuel cells.

Other experience or previous professions: Human resources, administration, finance and customer service

The best thing about my job is... Working closely with engineers and learning more and more about cutting edge technology.

The thing I like least about my job is... When there is more paperwork than hours in the day!

Other careers considered: Marine Biology, Web Design and Conservation

University of Cambridge

19. Computational Radiotherapy

http://www.voxtox.org, http://www.accelrt.org

Researchers from the High Energy Physics group at the Cavendish are working with engineers, radiotherapy physicists, radiographers and doctors in the University and in Addenbrooke's Hospital to improve ways of treating cancers with radiotherapy.

Radiotherapy

Radiotherapy refers to the use of ionising radiation to treat disease, particularly cancer. X-rays were discovered in 1895, and the first treatment of cancer with X-rays was performed in 1896. Since then the technology has changed considerably!

The term 'radio' used here is derived from the Latin 'radius' meaning a 'ray' or 'spoke'.

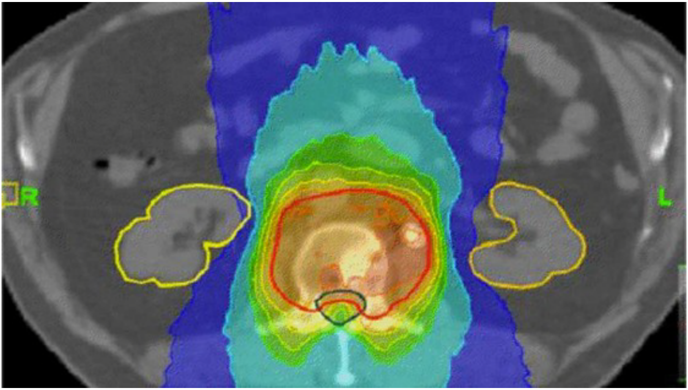
Today's radiotherapy uses high energy X-rays to destroy cancer cells. We have effective methods for delivering the radiotherapy to the target, to kill the cancer cells. Side effects occur because some normal tissue always lies next to, or even within the edge of, the tumour. Better targeting will reduce side effects, and make life better for patients.

Radiotherapy is becoming more and more effective as treatment systems develop in accuracy, hand-in-hand with developments in hardware and computing. Key goals of our research are to help better targeting of cancerous tumours and delivery of the right dose, reduction of side effects (toxicity), and the production of software to help do this.

Radiotherapy treatment

Three advanced approaches are being used which are generating enormous amounts of images and other data. This needs increasingly sophisticated handling so that it can be effectively labelled, stored and retrieved in a reliable and straightforward way. In planning the treatment, diagnostic images of the patient are combined with planning images to set the target areas for the radiotherapy beams. Each day, the patient is imaged in the treatment position and any corrections made before treatment – a process known as image-guided radiotherapy (IGRT). Treatment is delivered with Intensity Modulated Radiotherapy (IMRT), a technique to treat complex shapes, based on sophisticated computation. The TomoTherapy machine elegantly combines IGRT and IMRT in an integrated treatment solution.

🡩 ***Figure 1:*** *A TomoTherapy unit in Cambridge, at Addenbrooke's Hospital. This combines IMRT and IGRT approaches. (Credit: N.Burnet)*

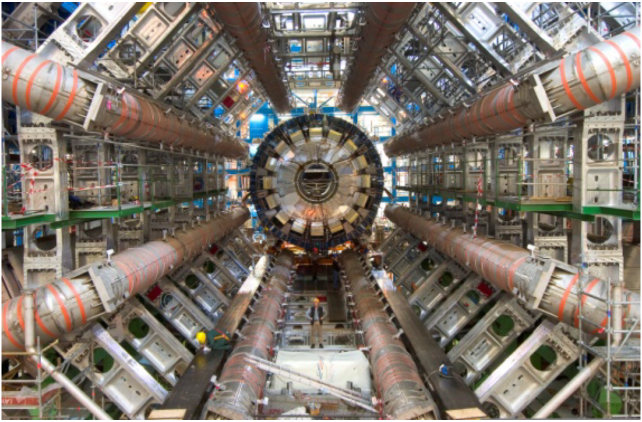


🡩 ***Figure 2:*** *Image-guided intensity modulated RT plan for a patient with a spinal tumour. (Credit: N.Burnet)*

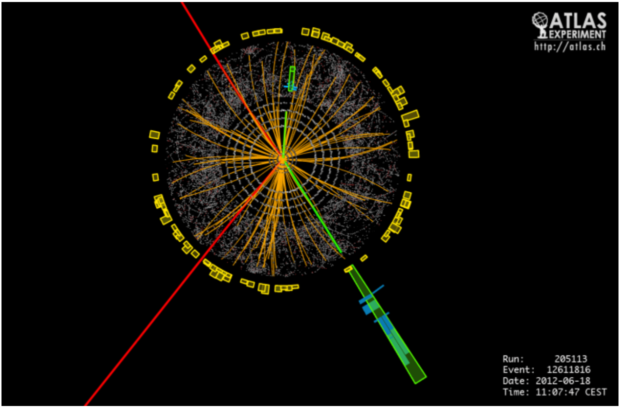
What's the link between high energy physics and radiotherapy?

The connection in our collaborations is through the computational side rather than the particle beam side. The Cavendish HEP group are contributing to the Large Hadron Collider experiments at CERN. Incredible quantities of data are generated from these experiments, generally as images of the particle collisions. So categorising and storing large volumes of data, often images, which require batch processing, is something in which HEP people have got a lot of experience. Advanced radiotherapy systems are also generating comparatively large quantities of image and other data which have to be categorised and stored, as well as processed.

We want to help radiotherapy specialists get easier access to the data without seeing all the stages of processing: in other words to make it as transparent as possible to the user. Data are therefore classified hierarchically and catalogued in a database. The use of metadata will allow relevant files to be selected for processing without human intervention. The user simply specifies the dataset in order to run the processing algorithm on all the relevant scans. A single pass through the data will require around 80,000 runs of the algorithm, presenting a problem of scale. Manual logging of the data flows, storage, and processing steps is clearly impractical, and we automate these tasks. The HEP group has extensive experience with distributed processing of large datasets, routinely running thousands of jobs on grid systems worldwide. The Ganga job processing framework [http://www.gridpp.ac.uk] was partly developed in Cambridge, to automate large job submission runs of this type.



🡩 ***Figure 3:*** *the ATLAS detector, at the Large Hadron Collider, CERN. (credit: CERN)*



↑ ***Figure 4:*** *example of an image of a candidate event (possible Higgs) from the ATLAS experiment. Vast numbers of images of particle collisions are captured and stored. (credit: CERN)*

What about engineering?

It's not all that easy to see how the internal organs move, and imaging them would help us to improve the radiotherapy. Engineers specialising in the modelling of materials and their properties are applying their techniques to modelling organs in the body. When a patient is having radiotherapy, they often have a number of sessions, called fractions, on different days. The cancer specialists prepare a radiotherapy dose plan based on the diagnostic images of the patient. But between fractions, the patient's organs may move. This could mean the radiotherapy will affect non-cancerous tissue. IGRT (image-guided radiotherapy) can track the position of the target before each treatment, ensuring the dose is delivered accurately. Better imaging of normal organs will improve this.

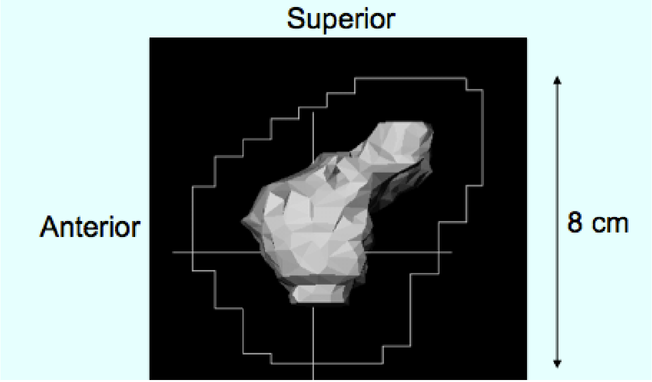


Figure 5: *Biomechanical model of a prostate (and seminal vesicles) ready to receive radiotherapy (credit: Y.Rimmer and A.Hoole)*

Exhibits

- Planning game: try your hand at creating a radiotherapy treatment plan. Starting from an image of a tumour, try to outline where it is and plan radiotherapy treatment.
- A body shell: this is used to position some patients for radiotherapy treatment.
- Images game: how many images can you match to the correct description?
- A tungsten target from a radiotherapy machine (one of the TomoTherapy units), showing damage to this extremely tough material. This is the result of the electron beam fired at it to generate the high energy X-ray beam.

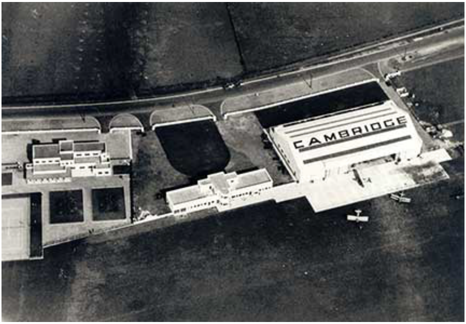
Links

HEP schools outreach pages:
http://www.hep.phy.cam.ac.uk/outreach/index.php

Physics in medicine pages:
http://www.insidestory.iop.org/

20. Marshall Aerospace and Defence Group

http://www.marshallgroup.co.uk/
http://www.marshallaerospace.com/



Short History Lesson and What Marshall ADG Does

Marshall of Cambridge was first established in 1909 by David Gregory Marshall, in a small lock-up garage in Brunswick Gardens, Cambridge as a chauffeur drive company. After the First World War Marshall became a dealership for Austin car's sales and it was towards the end of the 1920's that the son of David Gregory Marshall (Sir Arthur Marshall) graduated from Jesus College, Cambridge.

Sir Arthur learned to fly in 1928, and shortly thereafter created an airstrip near his family's Cambridge home, which by 1929 had turned into a full-fledged airfield. Six years later in 1937, Sir Arthur and his father, David, bought the land where the present Cambridge Airport now stands and started Marshall Aerospace. During World War II, Marshall's played a key role in training over 20,000 air crew.

Under Sir Arthur's guidance, the firm became the UK's largest aircraft repairer, fixing or converting 5,000 planes during the war. Over the years, such major airplane manufacturers as De Havilland, Bristol, Vickers and English Electric have entrusted Marshall's with the servicing of their aircraft.

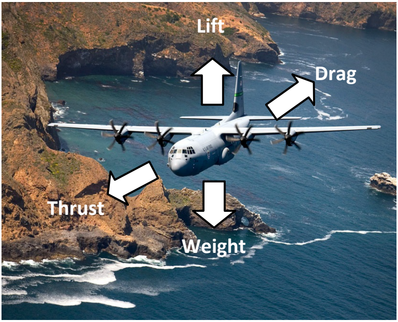
Marshall's company built, under subcontract, the famous droop nose for Concorde during the 1960's. During the 1980's Marshall's ties with the RAF were solidified by the conversion of C-130 Hercules to perform air to air refuelling in response to the Falklands Conflict, this vital modification was designed and installed on the aircraft within a fortnight.

The C130 aircraft is widely used by many air forces across the world and even civilian companies in every conceivable environment. It is widely recognised as the work horse of military forces, finding use in both supply and tactical missions, and is regularly seen flying in and out of Cambridge airport for its maintenance/modification inputs.

Today Marshall ADG has offices and staff placed all over the world. Each of these offices has their own speciality and was initially set up off the back of a contract with a customer, or purchase of an existing company. The site in North Yorkshire in particular was bought with the direct aim of providing Marshall with a share in the composite structure design and manufacturing market. The composites branch of Marshall ADG is now responsible for the manufacture of helicopter and fast jet pilot helmet outer shells, the gun shield on a type 45 frigate (Royal Navy), UAV airframes (Herti and Raven), along with various submarine, aircraft and even hovercraft structures. Similar to the pattern of metal airframes taking over from wood in the early years of aircraft development, the same trend is now being seen as metals are being replaced with composites.

In the simplest of terms Marshall ADG’s primary business is the modification, testing, repair and overhaul of aircraft and their sub-structures. The aerospace sector is one of the UK’s biggest industries and regularly exports more than £22bn worth of business every year the UK is still considered one of the world leaders when it comes to the Engineering sector which stems from a long history of achievements.

So how do aircraft fly?



When an aircraft is in flight there are four primary forces that act upon it, Lift, Weight, Drag and Thrust.

- Thrust is generated by the engines and propels the aircraft.
- Drag is the resistance caused by the aircraft forcing its way through the air at high speed.
- Weight is dependent on the aircraft size and what passenger/cargo content is being carried.
- Lift is the force created by air flowing over the wings at speed which then supports the weight of the aircraft.

Because of the nature of aircraft, achieving stability and balance in flight is no easy task but a vitally important one. Unlike driving a car on a tarmac road an aeroplane has no solid surface to help support its weight, air is constantly moving, changing pressure and likes to change speed constantly. This means that the distribution of lift and weight across the structure are very important for aircraft stability. Even the largest of aircraft like the Airbus A380 which is 72.72m (238ft 7in) long will require its centre of gravity to be within a range of a few meters of its ideal position. Weight distribution is one of the reasons why fuel is stored in a series of tanks throughout the wings of the aircraft, the fuel can be pumped to different tanks to redistribute weight and help balance the aircraft.

So when Marshall ADG are repairing or modifying an aircraft we must quite strictly record the changes made to the weight distribution. If the centre of gravity strays too far out of its safe range, the aircraft can become very difficult to control and in some rare cases become completely uncontrollable. This factor can be just as important as ensuring the aircraft structure is strong enough to perform the task it was designed for.

Some questions to think about:

Why did Concorde need a droop nose? No other plane at the time did.

How many countries operate C130 Hercules aircraft as part of their Air Force (roughly)?

Lift in more detail:

http://www.grc.nasa.gov/WWW/k-12/airplane/lift1.html

http://virtualskies.arc.nasa.gov/aeronautics/3.html

Name: Callum Ward

Position: Structural Analysis Engineer

Company: Marshall Aerospace and Defence Group

Educated in: Mexborough School and Sixth Form College, South Yorkshire

A-levels (or equivalent): Maths, Physics, Chemistry

University: University of Sheffield

Qualifications: MEng Hons, Aerospace Engineering

My day to day work involves... Assessing the structural integrity of repair schemes designed for C130 Hercules and L1011 Tristar aircraft, as well as advising designers on what repair schemes should be progressed with. This work is primarily desk and meeting room orientated but the aircraft I work on are usually right next door to the office so I take the opportunity to visit them regularly. My job role is defined by the department I'm currently based in which is my 3rd department in the 3 years I've been at the company.

Other experience or previous professions: Part time Retail work, Specialist Cleaning Firm, part time Research Engineer.

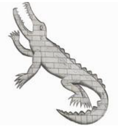
The best thing about my job is... Seeing tangible results from my day to day efforts.

The thing I like least about my job is... Industry politics, bureaucracy

Other careers considered: Pilot, Officer in the Armed Forces, Motorsport/Motor vehicle Engineer

Cavendish Laboratory

21. Laboratory for Scientific Computing



http://www.lsc.phy.cam.ac.uk

What is scientific computing?

Scientific computing can be used to study anything from the behaviour of atoms in a crystal, to the motion of hurricanes, to the mechanics of black holes.

When scientists study the natural world they do experiments and make observations. From these observations they come up with mathematical equations, or models, which describe physical phenomena. These models can be anything from classical models like Newton's laws of motion, to quantum mechanical models like the Schrödinger equation. The job of scientific computing is to solve these equations on a computer and look at how the models behave. This involves a mixture of physics, chemistry, mathematics and computer science.

How do fluids work?

If you watch the weather report on television, you will see a map which shows a prediction of how rain clouds and temperature fronts are going to behave. How do meteorologists come up with these predictions?

The atmosphere behaves like a huge fluid, constantly in motion and exchanging heat and mass with the ocean. This type of system is modelled with a branch of physics called fluid mechanics. The equations of fluid mechanics are simple – you can write them down in a few lines. You can use them to describe the mixing of milk into a cup of coffee, or the detonation of an explosive gas, or the motion of a hurricane, or the airflow over an aeroplane's wings. A lot of the work done by LSC involves fluid phenomena like these. But solving these equations for a particular case is hard. And for complex fluid systems, there are processes which must be modelled in addition to the fluid mechanics, such as chemical reactions and thermodynamics.

How do you predict properties of materials?

The atmosphere model described above needs to represent properties of water and air in a realistic way – for example, how they behave under changes

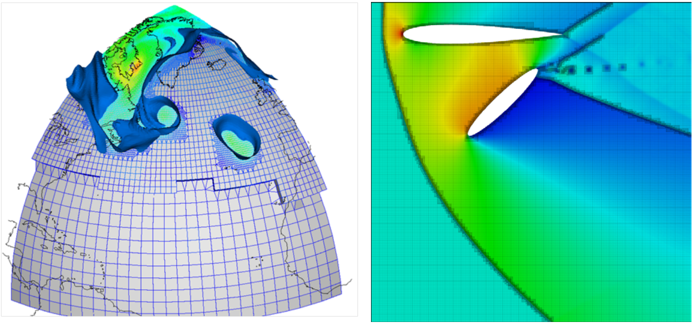


Figure 1: *Left: part of a global atmospheric simulation. Right: supersonic flow over a payload dropped from an aerofoil.*

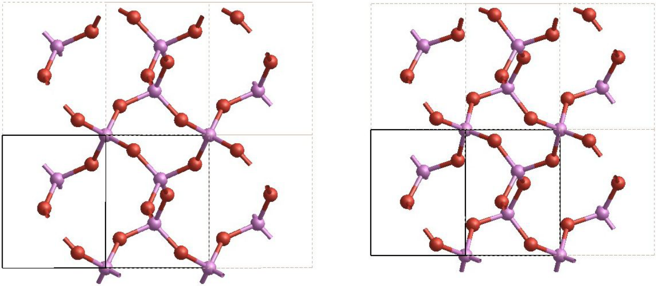
of pressure or temperature. Other simulations will likewise need to know how a particular material changes shape or size when it is put under stress. Rocks, paper, steel, aluminium or other materials will all behave differently. This type of behaviour is described by a model called an 'equation of state'.

Sometimes simple models (such as an 'ideal gas') work well. Other times, equations of state are fitted to experimental measurements. Computer 'experiments' are also a useful source of information. Methods based on quantum mechanics can predict the balance of forces present in a crystal, and hence an equation of state for the crystal.

For example, the figures on the next page show the predicted atomic structures of quartz at atmospheric pressure and at 10GPa (about 100,000 times atmospheric pressure).

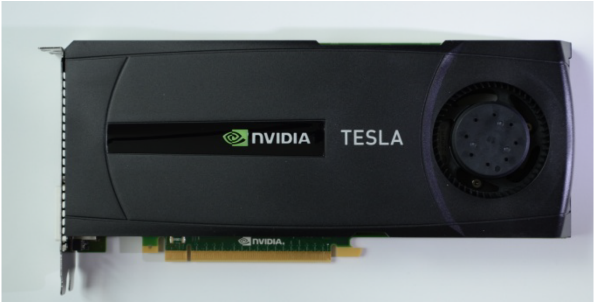
How do you find solutions faster?

Scientific computing is a multi-disciplinary field. Thinking about science problems is only one part of the field. Another part is thinking about programming and computer science problems. One big problem is how to solve equations quickly. It's no use having a brilliant computer model of a hurricane if it takes years and years to give a prediction. For this reason scientific computing takes place near the forefront of high performance computing technology.



↑ ***Figure 2:*** *Repeating unit of quartz crystals at atmospheric pressure (left) and 10GPa (right)*

In the demo you will see a technology called GPU computing. GPU stands for Graphics Processing Unit, which is the graphics card in your computer. The GPU is normally used to draw images and 3D graphics on your computer screen. If you play modern PC games then you probably have a powerful GPU in your computer. GPU computing uses graphics cards to calculate useful scientific results, like the fluid and crystal simulations above. In some situations it can be much faster than the regular processor in your computer.



↑ ***Figure 3:*** *An NVIDIA Tesla graphics card, one of the first GPUs designed specifically for general purpose and scientific computing.*

Name: Sean Lovett

Position: PhD student at the Cavendish Laboratory (studying fluid flow in porous media)

Educated in: Wimbledon College and King's College schools in London

A-levels (or equivalent): International Baccalaureate

University: Selwyn College, Cambridge

Qualifications: BA in Maths, MPhil in Physics

My day to day work involves... computer programming, doing mathematics with a pencil and paper, reading journal papers, writing, answering emails. I also have meetings with my supervisor and an external industrial scientist with whom I collaborate.

The best thing about my work is... When an idea works better than expected.

The thing I like least about my work is... Bugs in my computer code.

Careers considered: Scientist (industrial or academic), programmer

22. Mott MacDonald

http://www.mottmac.com/

The power of water

The Mott MacDonald Group is a diverse management, engineering and development consultancy delivering solutions for clients world-wide. The Water and Environment Division is involved in projects across the world including reservoirs, pipelines, coastal defence and irrigation.

The force of water is regularly brought to our attention by natural disasters such as tsunamis and flooding. However, it was realised long before electricity that the force of water could be harnessed in order to provide power and this was used to drive mills as long ago as ancient Greek and Roman times.

Hydropower

With reserves of fossil fuels rapidly depleting, renewable sources of energy are going to be increasingly relied upon to provide the power we need. In 2008 renewable energy supplied around 13% of the world's energy consumption; of this approximately 17% was hydropower.

🡅 ***Figure 1:*** *Mott MacDonald monitored dam and tunnel construction for the 690MW hydroelectric development at Kárahnjúkar, Iceland.*

Hydropower utilises energy from water as it falls from a higher elevation to a lower elevation. This is most commonly seen on dams where the potential energy is stored by forcing water to build up behind the dam. A limited amount of water is allowed through and turbines are used to obstruct the path of the water, causing energy transfer to take place. The force of gravity acting on the water causes it to drive the turbines from which the energy can be collected and stored.

“Water hammer”

A key challenge faced by water engineers is surge within pipelines. If a valve on the pipeline is closed or opened rapidly there is a change in velocity of the liquid and a pressure wave is caused through the liquid in the pipeline. This pressure can cause the pipe to crush or burst in order to equalise the pressure inside and outside the pipe.

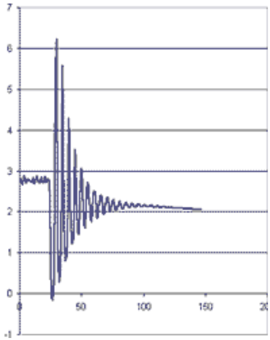


Figure 2: *Pressure in a pipeline due to a surge or “water hammer”*

Surge is not only a problem in large pipelines but also in plumbing in houses. When a tap is turned off, or an appliance closes a valve, this causes a change in pressure in the pipes. This can be observed in older houses as the change in pressure causes the pipes to vibrate. This effect is known as “water hammer.”

Household water systems are built with air cushions, vertical sections of pipe filled with trapped air. A valve is closed; the pressure wave moves along the pipe through the less compressible water; it then reaches the air cushion and the energy can be dissipated. If the surge is successfully dissipated then no damage is caused to the pipeline.

The physics of both hydropower and surge rely on Newton’s Second Law of Motion:

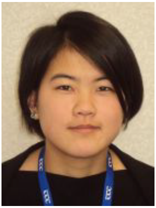
$$Force = mass \times acceleration$$

or

$$Force = mass \times (change\ in\ velocity\ /\ change\ in\ time)$$

As shown by these two examples, the force of water can be used greatly to our advantage and in the future could be the main renewable energy source used to provide power. However, it can also cause problems and this can lead to destruction both from natural disasters and human activity.

Name: Charlene Chung



Position: Graduate Water Sector Analyst / Statistician

Educated in: Portree High School, Isle Of Skye

A-levels (or equivalent): Maths, Physics, Biology, French, English, Modern Studies

University: University Of Strathclyde and Heriot Watt University

Qualifications: BA Hons Mathematics and MSc Water Resources and Catchment Management

My day to day work involves... Analysing data over different types of projects and mathematical techniques to solve engineering problems. I build mathematical models that are used to forecast the risk involved in a number of water engineering projects, like pump failure and costs affected. I also do a lot of computerised hydraulic modelling which involves using site survey and questionnaire information and merging that with a computer simulation of an area, which is predicted to flood over a period of time. Computer models of scenarios are built and used to forecast the impact this will have over time. These two involve a lot of problem solving skills, engineering judgment and statistical analysis.

The best thing about my job is... Being able to apply maths to problems in water engineering and prove that it can actually be used for pretty much everything in the industry (maths really isn't boring!!)

The thing I like least about my job is... Some of the endless days in front of the computer processing data.

Other careers considered: Oceanographer, Medical statistician

Name: Flora Keen

Position: Water Engineer

Educated in: Wykeham House School and Havant College, Hampshire

A-levels (or equivalent): Maths, Physics, Chemistry, Biology

University: Cardiff University

Qualifications: MEng in Civil Engineering

My day to day work involves... carrying out studies and design for the water industry. There is a lot of variety in my job so what I do day to day depends on the project that I am involved in. Anything from carrying out modelling of water networks, calculations for design or preparing drawings to writing reports, going to client meetings and giving presentations.

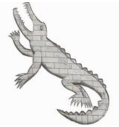
The best thing about my job is... Working with a team of people, the variety and interesting work on offer.

The thing I like least about my job is... Deadlines.

Other careers considered: Doctor, Geologist or something else science related.

Cavendish Laboratory

23. High Energy Physics Group



http://www.hep.phy.cam.ac.uk

Scatter!

In 2012, CERN announced the discovery of the Higgs boson produced in high energy proton collisions in the Large Hadron Collider. Ultra-high energy proton-proton collisions like these reveal interactions that were prevalent soon after the creation of the Universe. Studying these interactions requires highly sophisticated apparatus that allows us to measure the tracks of individual particles that are invisible to the naked eye.

In this session we will explore some ways of detecting in the lab particles like the ones that will be detected by the LHC experiments. Naturally occurring high energy particles constantly bombard the Earth and we will demonstrate how we can detect these “in front of your very eyes”. We call these particles from beyond the Earth “cosmic rays”.

The energies of cosmic ray particles span an enormous range and the wide variety of particle energies reflects the wide variety of sources.

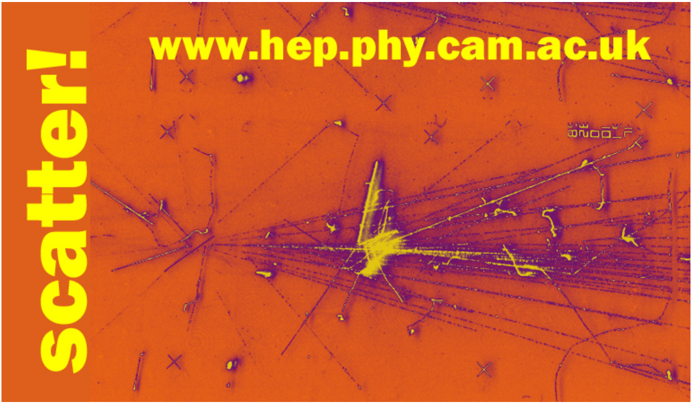
Almost 90% of cosmic ray particles are protons, about 9% are helium nuclei and about 1% are electrons. They are able to travel at close to the speed of light from their distant sources to the Earth because of the low density of matter in interstellar space.

But when cosmic ray particles reach the Earth the atmosphere appears like a solid wall to them and they immediately collide with molecules to produce a cascade of lighter particles 10km above our heads. Some of these new particles, created from the energy of the incoming cosmic ray, are of a type we call muons.

Muons are special because they do not interact strongly with the atmosphere and therefore we would expect them to reach the surface of the Earth where we will detect them. However, they are unstable and decay after about 2 microseconds when not moving. The muons that we detect are travelling at typically 0.9998 times the speed of light; it is only by invoking Albert Einstein’s theory of relativity for fast moving objects that we can explain how the muons are able to reach the ground before they decay.

At CERN we use very large, very fast detectors capable of recording the paths of thousands of particles 40 million times per second. Nearly all particle detectors work by detecting the very weak disturbances to the surrounding atoms as the high energy charged particles pass through. In this session you will see how we can exploit these effects to detect cosmic ray muons and the particles produced in naturally occurring radioactive decays in two different detectors.

You will see cosmic ray muons being detected in a spark chamber where the path of the muon is revealed by sparks that jump between metal plates, arranged in a stack, at very high voltage. You will also see the paths of lower energy particles produced in radioactive decays revealed as trails of droplets in our cloud chamber.



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