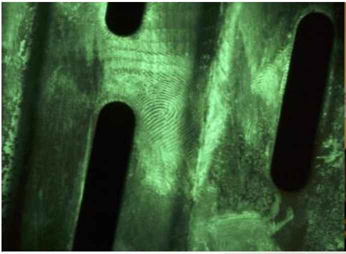
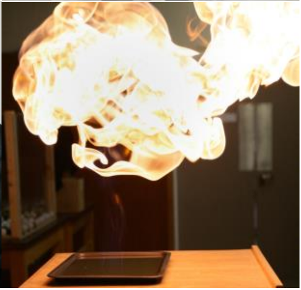
# THE CAVENDISH LABORATORY

# Physics at Work 2015





# Exhibitors List 2015 (in route order)



**We would like to thank everyone who has given their time and expertise so generously to this event.**

IOP | Institute of Physics
East Anglia Branch

THE CAVENDISH LABORATORY

&

# THE CAMBRIDGE PHYSICS CENTRE

Present the

# 2015
# PHYSICS AT WORK EXHIBITION

at the Cavendish Laboratory,
Madingley Road, Cambridge

On

**Tuesday 22nd September**
**Wednesday 23rd September**
**Thursday 24th September**

**Organised by:**

Dr. Lisa Jardine-Wright and Jacob Breward Butler
Educational Outreach Department, Cavendish Laboratory

**Facilities and Technical Assistance:**

The Cavendish Laboratory

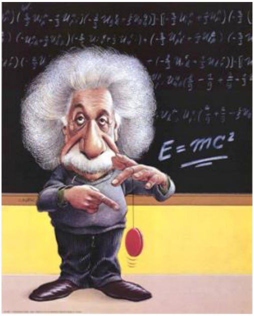
**Also sponsored by:**

The MathWorks™ Accelerating the pace of engineering and science

ttp

# PHYSICS AT WORK 2015

## 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 2015 Physics at Work Exhibition will give you an 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](http://www.physics.org)

## Cavendish Laboratory

# 1. Semiconductor Physics Research Group

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

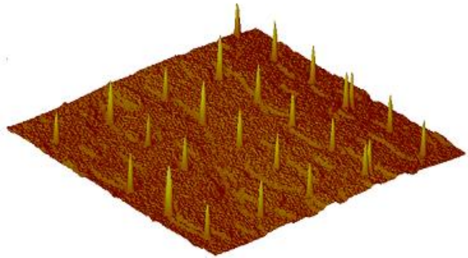
Electricity seems very simple – you just flick a switch and there it is – but how often have you thought about what is happening to the electrons that make up that electricity? The electrons' behaviour can change depending on what material they are in. Materials can be divided into three categories according to their ability to conduct electrons: insulators, conductors and semi-conductors. 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 semi-conductors 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, as they are 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 academic research, our work leads to faster, more energy efficient semiconductor devices and even brand new devices.

## Few dimensions and quantum mechanics

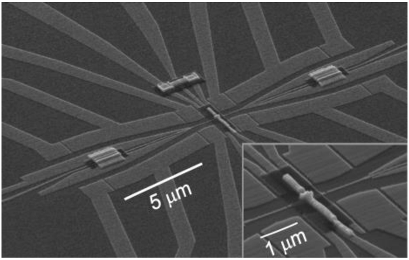
Our group specialises in the physics of electrons confined to two, one or zero dimensions. Electrons can be made to travel in two dimensions by stacking layers of different semiconductors, effectively trapping the electrons at the boundaries between the layers. We can also apply electric fields to the stacked layers of semiconductors to force the electrons to travel along only one direction (1 dimensional) or not allow them to move in any dimension at all (0 dimensional), which gives us quantum dots.

Some of us study low dimensional electron transport in semiconducting materials that naturally show one- and two-dimension properties, such as GaAs/AlGaAs heterostructures, and graphene (single layers of graphite). 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.



🡐 ***Figure 1:***
*An array of InAs quantum dots growth by MBE technique. By apply an electric field, the electrically driven single-photon source is generated*

***Figure 2:***🡒
*A surface-acoustic-wave electron interferometer, created using electron-beam lithography. This method can be used to create features at a nanometre level. The thin "fingers" of metal are over 1000x thinner than a human hair.*




However we do it, the electron behaviour is very different compared to that in three dimensions. 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 wave diffraction patterns).

## 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 that unwanted atoms do not change the properties of the finished structure.

**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

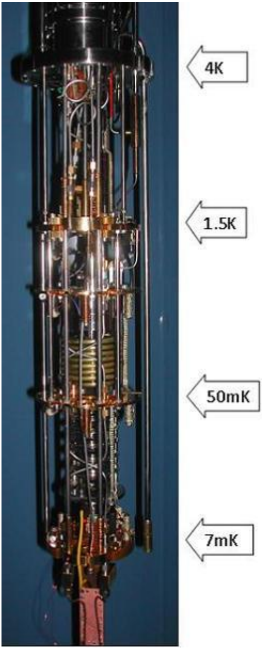
**Current job**: 1992-date Semiconductor Physics Group, Physics Department, University of Cambridge. I am responsible for the maintenance of the SP cleanroom including repairing equipment, ordering supplies, managing cleanroom suits and helping people outside of SP who want to use our cleanroom. I also 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.

## Measuring at very low temperatures




🡐 ***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.*

Most of the experiments we do in Semiconductor Physics are resistance measurements, in which we observe 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.

## University of Cambridge

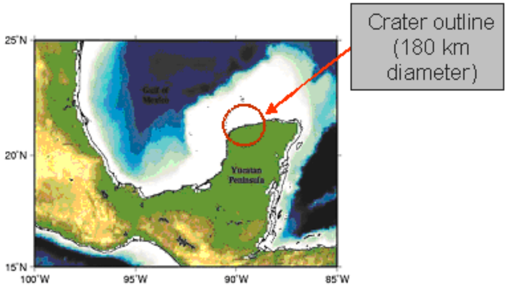
# 2. Earth Sciences (Dept. Of)

## Bullard Laboratory

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

### Seismics - A look at Global Catastrophe

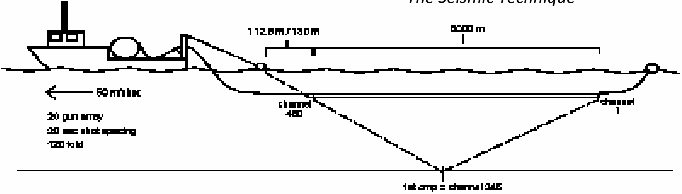
Sixty-five million years ago a 10 km diameter meteor crashed into the Yucatan Peninsula of Mexico leaving a 200 km wide crater. This crater is known as the Chicxulub crater (it is named after the small fishing village that is now at its centre). It is one of only three known impact craters on Earth with 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.

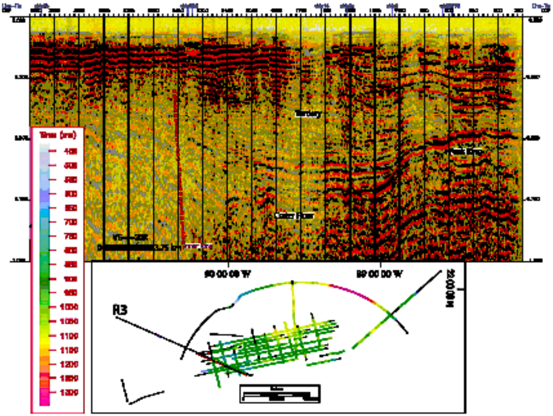



The University of Cambridge has recently been involved in the largest seismic survey of the crater, involving over a month of seismic shooting and recording with hundreds of receivers on the seabed and on land. Preliminary results show the exciting sectional views of the crater, which we will be presenting.

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*

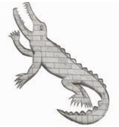



*Preliminary seismic section from 2007 experiment.*

Cavendish Laboratory

# 3. Astrophysics Research Group

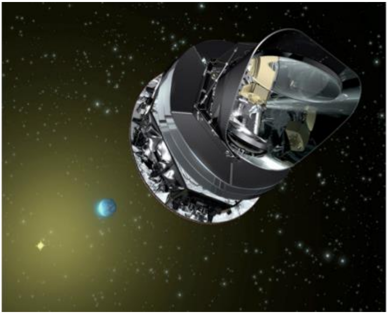


http://www.mrao.cam.ac.uk

## 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 – 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.

We are also working on a telescope called "The Square Kilometer Array" or SKA. This will be a huge ground-based radio telescope with over a million square meters 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 comparing the signals from different dishes in the array, astronomers are able

🡅 ***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*

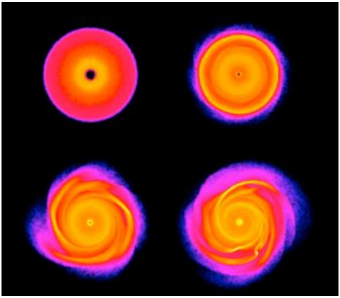
to build up very detailed maps of the objects in the sky that shine at radio wavelengths.

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****: The 66 high-precision dishes of the ALMA array.*
*Credit: ESO/Clem & Adri Bacri-Normier*

We also work on another new telescope called ALMA, which is located in Chile. The 66 dishes of ALMA work at relatively high radio frequencies. ALMA is 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.

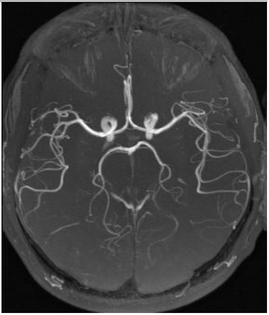
**Other careers considered:** Physicist, Aeronautical engineer.

# 4. Wolfson Brain Imaging Centre

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

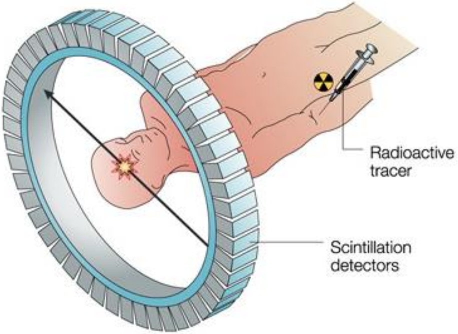
## Brain imaging

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).

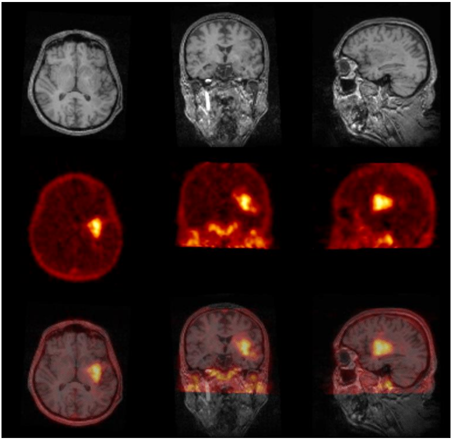


🡅 ***Figure 1:*** *From top left (going clockwise):*

*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

# 5. Atomic Weapons Establishment

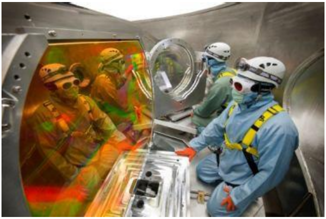
http://www.awe.co.uk

## Explosive Energy

The Atomic Weapons Establishment (AWE) plays a crucial role in the defence of the United Kingdom by providing and maintaining the nuclear deterrent of the UK. 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.


*Photos by LA(phot) Mez Merril and LT Stuart Antrobus RN*

Energy is all around us in many forms; heat, sound and light are all forms of energy. Energy isn't something we can create; it is a conserved quantity across the whole universe, meaning that 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.



There are many different forms of energy that we interact with every day. Light as a form of energy can be very powerful, heating solar panels or providing the energy for chemical reactions that cause sunburn.

Lasers convert electrical energy to light; through the use of special materials and mirrors a laser continually outputs a steady stream of identical light particles called photons. The energy of the light is determined by the material used and is the cause of the colours that we see.

The word laser is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Lasers are used in a wide variety of applications, including CD/DVD players, high end optical electronics and in the physics experiments undertaken at AWE in the Orion facility.

Lasers can have low energy compared to a standard light bulb of 60 Watts (W) but they focus all of their energy on a very small area. While a light bulb lights a room a laser delivers energy only in a few millimetres making them ideal for applications requiring a very high energy-density.

Increasing the energy (and energy density) allows lasers to be used for different things. The power of a typical laser pointer is around 1mW, and the laser in a CD/DVD player delivers roughly 5mW. Lasers can also be used for surgical applications delivering around 30W to 100W and in industrial applications lasers can even cut metal with outputs as high as 3000W. In contrast, facilities such as the Orion laser at AWE can deliver power outputs of the order of Peta Watts (1,000,000,000,000,000 Watts)!

The high energy-density conditions generated by the Orion laser allow scientists to study matter in regimes not easily obtainable on Earth. At these very high temperatures and densities materials become plasmas and interact differently. In particular, it allows plasma physicists to study the thermonuclear reactions that take place in stars under such extreme conditions, but on a much smaller scale.

We are going to show you the difficulty of conducting an experiment with lasers, working together as a team to complete the experiment. We will all have some fun learning about lasers in this interactive demonstration.

**Name**: Adam Wardlow

**Position:** High Temperature Material Modeller

**A-levels:** Mathematics, Physics, Design-Technology

**University:** University of Nottingham and University College, Durham

**Qualifications:** MSci in Mathematical Physics and Ph.D. in theoretical high-energy particle theory

**My day-to-day job involves:** Development and use of computer models to calculate high-temperature equations of state and material data

**The best thing about my job is:** Collaborating with experts in the field, drawing from their many years of collective experience, to develop new and innovative models and codes

**Name**: Mike Rowlands

**Position:** Operational Analyst

**A-levels:** Mathematics, Physics, Chemistry

**University:** University of Surrey

**Qualifications:** BSc in Physics and MSc in Radiation Physics

**My day-to-day job involves:** Analysis of experimental data and computer models

**The best thing about my job is:** Being surrounded by experts allows me to learn and develop every day. My work is interesting and varied and allows me freedom in which direction I take my career.

**Name**: Matt Fidler

**Position:** GIS Engineer

**A-levels:** Geography, Physics, Computing

**University:** University of Plymouth

**Qualifications:** BA Hons in Geography

**My day-to-day job involves:** Configuring AWE's utility and facility assets and providing geospatial analysis and mapping to various on-site departments including the police and emergency response teams.

**The best thing about my job is:** Being able to work with a multitude of stakeholders and see the end product served out to the business on a visible platform; with anyone able to access and utilise our work.

**Name**: Emma Stubbs

**Position:** Analytical Scientist

**A-levels:** Chemistry, Physics, History

**University:** Loughborough University

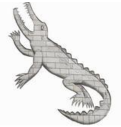
**Qualifications:** MChem in Chemistry and Analytical Chemistry and a Chemistry Ph.D.

**My day-to-day job involves:** Analysis of Explosives and reporting data

**The best thing about my job is:** Working with lots of fun materials and doing really exciting experiments which I never thought I'd get paid to do for a living!

## Cavendish Laboratory

# 6. Surface Physics Group: STMs



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

### Why study surfaces?

Every solid has a surface, and surfaces play a huge role in physics. These are a few reasons why we are interested in studying them:

### Catalysis

Some surfaces act as catalysts, speeding up or enabling reactions when the molecules involved adsorb (stick) on them. These catalysts are very important in industrial processes, such as the manufacture of chemicals. Another important example is the catalytic converters found in cars, which contain platinum, to catalyse the conversion of the toxic components of exhaust. Understanding how reactions proceed at surfaces is crucial to designing effective catalysts.

### Friction

Friction affects our everyday lives, but what are its origins at the atomic level? How do the forces between surfaces at an atomic level affect the larger scale behaviour of a system? As advances in technology allow electronic and mechanical components to become ever more miniaturized, these become important questions, and understanding how friction occurs between surfaces at a molecular level is essential.

### Material properties

Often, the properties of a material, such as its electrical or thermal conductivity, change dramatically between the bulk (inside the material) and the surface. To properly understand the behaviour of materials, the surface properties, as well as the bulk, must be studied.

## Studying surfaces

A variety of techniques are used to study surfaces at the atomic level, making use of electrons, atoms, neutrons and infra-red light as probes. Here we touch upon two important ones.

## Scanning tunnelling microscopy – seeing surfaces at the atomic level.

In a scanning tunnelling microscopy experiment, a metal tip is held above a conducting surface, with a gap (the size of a few atoms) between them. When a voltage is applied to the probe, an electrical current flows between the tip and sample. This is surprising-how can a current flow when there is a gap? To understand this, we need quantum mechanics, an area of physics which becomes important when considering things on atomic scale or even smaller. In quantum mechanics, it is possible for a particle to penetrate, or 'tunnel' through, a barrier which, according to classical, 'everyday', physics should be impossible. In this case, electrons are tunnelling and the 'barrier' is the vacuum between the tip and sample. The size of the tunnelling current depends on the number of electrons at the surface, so by scanning the tip across the surface and recording the current at each point, we can build up a map of surface electron density. Electrons tend to form a 'cloud' around atoms, so the electron density maps can be interpreted to determine the structures formed by atoms at surfaces.

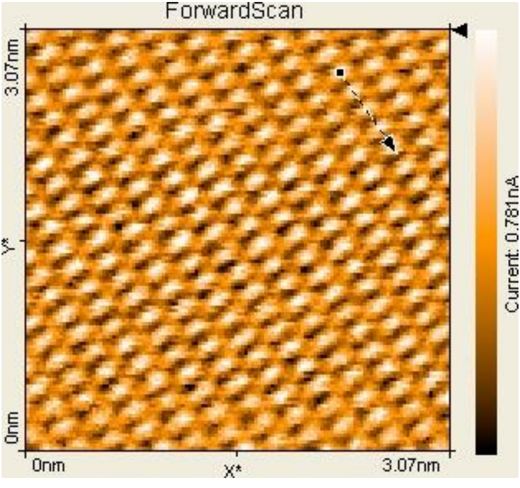



***Figure 1:*** *STM image of a graphite surface, recorded during a third year undergraduate practical, showing the hexagonal arrangement of atoms on the surface.*

## Helium atom diffraction - using atoms as diffracting waves.

You may have come across the idea that light can be diffracted, for example when it bends around obstacles. Significant diffraction occurs when the obstacle encountered is similar in size to the light wavelength.

A consequence of quantum mechanics is that particles can exhibit wave like properties. The discovery of this wave-particle duality was an important milestone in the development of quantum mechanics over a hundred years ago. The wavelength of matter is called the de Broglie wavelength, after one of the scientists behind the discovery.

Helium atoms have a de Broglie wavelength of about 1 Å (angstrom = $10^{-10}$ m, a ten thousand millionth of a metre), which is close to the spacing between atoms on a surface. Therefore, a helium atom can be thought of as a wave, which has the right wavelength to undergo diffraction when it hits a surface of atoms. In a typical helium scattering experiment, a beam of helium atoms travelling at about 2000 m per second is scattered from a surface and detected using a mass spectrometer. From the way the helium atoms diffract, we can determine the structure of the surface at an atomic scale.

Atoms or molecules with a similar mass to helium can also undergo diffraction from surfaces, but helium is a particularly useful and widely used probe since it is inert (unreactive) and neutral (no net electronic charge) and therefore scatters from the surface without damaging or affecting it in any way.

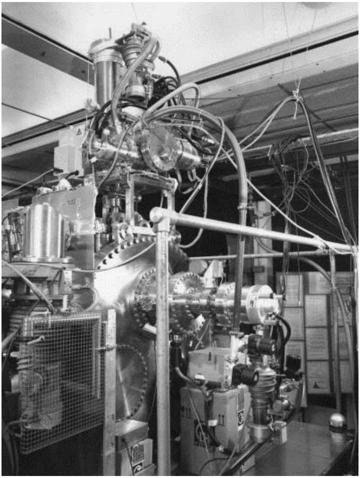


***Figure 2:*** *Apparatus used for helium diffraction experiments. The sample is contained in the large central chamber and the detector is at the top. The experiment must be performed in a vacuum and attached to the chamber are various pumps for evacuating it.*

## 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?

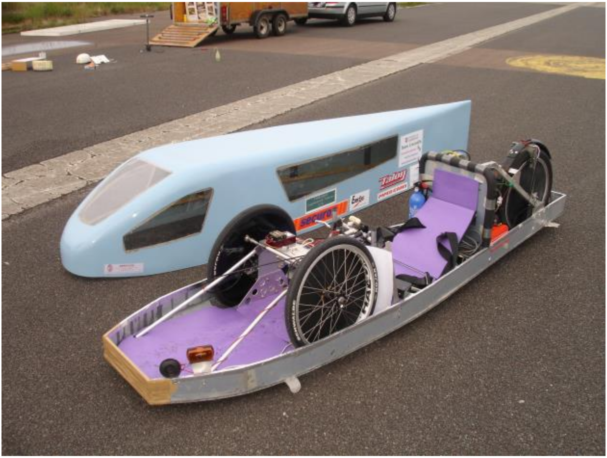

**🡡 *Figure 1:*** *Team Crocodile's Fuel-Efficient Car & Drivers*

- **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 2015 will be available at the Physics at Work 2015 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.

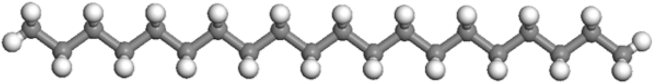
Polymers are more than just plastic bags, packaging or toys. They can be designed to dissolve in water, conduct electricity, or change colour or shape with the application of an electric field or heat. Polymers have always been around; natural polymers include the proteins that make up all living things, cellulose, starches, wood, silk, wool and natural rubber. It wasn't until the early 19$^{th}$ 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 2: Polyurethane has a vast array of applications.*

🡅 ***Figure 3:*** *PVA glue, otherwise known as 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$^{o}$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

**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

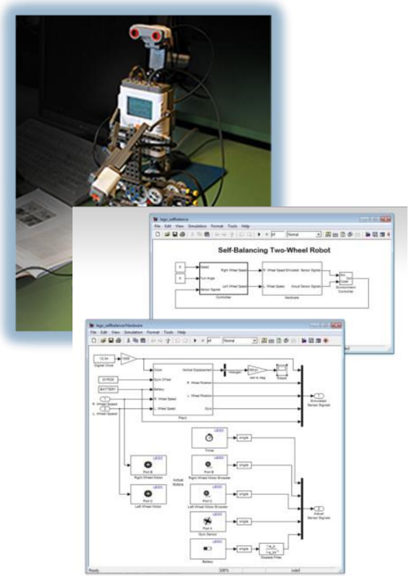
http://www.mathworks.co.uk

### 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 simulate, visualise, and analyse data from their experiments, 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, machinery for industry, 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” experience working with both 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 popular 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 allows 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 building an actual implementation.

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

**Name:** Dr Gareth Griffiths

**Position:** Software 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)

**Name:** Dr Andrew Powell

**Position:** Software Developer

**Company:** MathWorks

**Educated at:** Corfe Hills School, Dorset

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

**University:** Imperial College, London & Herford College, University of Oxford

**Qualifications:** MSci, Physics (Imperial), DPhil in Experimental Particle Physics (Oxford)

**My day to day work involves...** working within a small team of fellow Software Developers and Quality Engineers to design and develop robust software features for future versions of MATLAB and Simulink.

**Other experience or previous professions:** Previously I was a STFC research fellow, based at the University of Oxford, conducting research upon data obtained from the LHC particle-physics experiment at CERN.

**The best thing about my job is...** working with an incredible set of smart, talented people in order to develop software tools that will bring benefits to lots of scientists and engineers all around the world.

**The thing I like least about my job is...** not having enough time to work on all the exciting projects I wish I could work on!

**Other careers considered:** Medicine, Teaching, Finance.

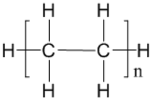
Cavendish Laboratory

# 10. Optoelectronics Research Group

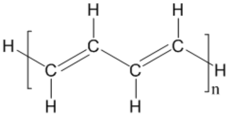
http://www.oe.phy.cam.ac.uk

## Conduction in Polymers

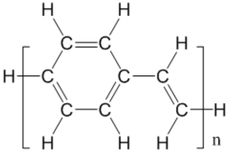
Look around you and you will find a diverse range of things, from cling film to artificial limbs, made from plastics. Plastics themselves are made from long chain organic molecules consisting mainly of hydrogen and carbon arranged in different ways (*figure 1*). Most of these well-known plastics are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



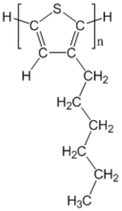
a) Polythene



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)*

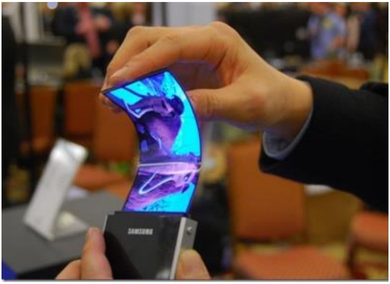
positive charges. Conventional solar cells are made from silicon, which is costly to process, but polymer solar cells can be produced very cheaply and large arrays will be able to bend flexibly around objects or roll up for ease of transportation (*figure 3*).

## 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.

## 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...** analysing 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

**Educated in:** University of Manchester (BSc Hons in Physics with Technological 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 prevents contamination of my samples.

**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

# 11. British Antarctic Survey (BAS)

http://www.antarctica.ac.uk

## Ozone Measurements in the Antarctic

Ozone is a gas consisting of three oxygen atoms and 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.

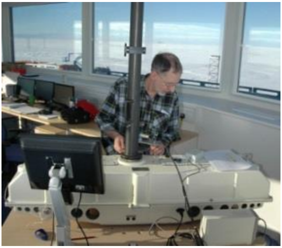
BAS scientists discovered the Antarctic ozone hole over twenty-five years ago and continue to study its annual formation and disappearance. The "Hole" varies in size and duration from year to year, depending on the "weather" in the upper atmosphere. The 2015 hole will be nearing its deepest as Physics 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:** Mr Steven Colwell

**Position:** Meteorologist

**Company:** British Antarctic Survey

**Educated in:** Cannon Slade School, Bolton

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

**University:** Coventry

**Qualifications:** BSc in Physical Science

**My day to day work involves...** answering questions about the meteorological data that we hold. Building and testing meteorological equipment and then installing it in Antarctica. Travelling to conferences in foreign countries and visiting schools to promote what BAS does in Antarctica.

**The best thing about my job is...** trips to Antarctica.

**The thing I like least about my job is...** dealing with paperwork.

**Name:** Rosey Grant

**Position:** Meteorologist

**Company:** British Antarctic Survey

**Educated in:** Cranbrook School, Kent

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

**University:** University of Bath, University of Leeds

**Qualifications:** MPhys, PhD in atmospheric physics

**My day to day work involves...** I spend the Antarctic summertime in Antarctica and the British summertime in Britain. While in Antarctica I collect and monitor long term meteorological data. I also assist with flying operations by taking weather observations. When I am back in Cambridge my time is spent preparing for the next season and training up the new meteorologists ready for Antarctica.

**Other experience or previous professions:** Fieldwork in UK, Europe, America and Arctic.

**The best thing about my job is...** spending time in Antarctica and learning more about Antarctic meteorology.

**The thing I like least about my job is...** packing, unpacking, packing, unpacking, packing....

**Other careers considered:** Motorsport engineer

**Name:** Jonathan Shanklin

**Position:** Emeritus Fellow

**Company:** British Antarctic Survey

**Educated at:** King's School, Chester

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

**University:** Magdalene College, Cambridge

**Qualifications:** MA (Natural Sciences), PGCE in Physics

**My day to day work involves...** I am one of the scientists who discovered the Antarctic ozone hole. I was responsible for the weather and ozone measurements in the British Antarctic Territory, which included testing equipment, processing data, writing reports, attending scientific meetings and visiting Antarctica. I continue to monitor the climate and ozone data from Antarctica.

**Other experience or previous professions:** Geology field work, optical research

**The best thing about my job was...** going to Antarctica.

**The thing I liked least about my job was...** dealing with paperwork, but now that I'm retired I can avoid most of it.

**Other careers considered:** Astronomer

**Name:** Tim Barnes

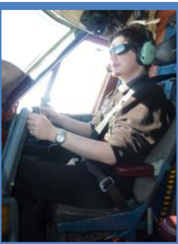
**Position:** Data Manager

**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

# 12. 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...

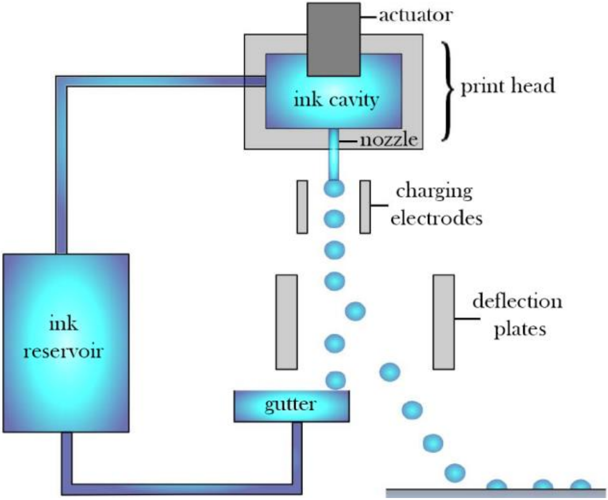
Domino was founded in Cambridge in 1978. Not long afterwards EU legislation was introduced requiring all food products to be marked with a best before date. Continuous ink-jet printing provided a perfect solution, as it is fast and doesn't involve contact between the printer and the product.

## 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!

# 13. Rolls-Royce

http://www.rolls-royce.com


## What we do

Rolls-Royce creates power. Better power for a changing world!

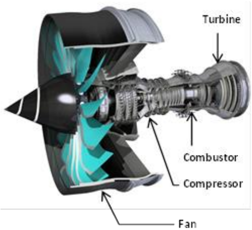
Rolls-Royce designs, develops, manufactures and services integrated power systems for use in the air, on land and at sea.

We are one of the world's leading producers of aero engines for large civil aircraft and corporate jets, and are the second largest provider of defence aero engines and services in the world.

For land and sea markets, reciprocating engines and systems from Rolls-Royce are in marine, distributed energy, oil & gas, rail and off-highway vehicle applications. In nuclear, we have a strong instrumentation, product and service capability in both civil power and submarine propulsion.


## Gas turbine technology

- A gas turbine can accelerate air to create thrust (jet engines), drive generators to make electricity, or turn pumps and ship propellers (industrial / marine gas turbines).



- Gas turbines convert the energy from burning fuel via three main elements – a compressor, combustor and turbine.
- Gas turbines have a higher power density than internal combustion engines.

### Fans

The fan in a gas turbine produces 80 per cent of the engine's thrust, as well as feeding air to the gas turbine core.

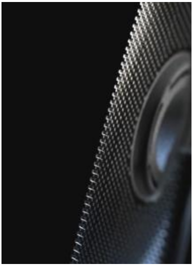
The hollow, titanium wide-chord fan blade, pioneered by Rolls-Royce and introduced into airline service in the 1980s, set new standards in aerodynamic efficiency and resistance to foreign object damage. Since that time we have continued to innovate and improve them.

Fan efficiency is an increasingly important contributor to overall improvements in engine efficiencies.

## Compressors

The primary purpose of the compressor is to increase the pressure of the air through the gas turbine core. It then delivers this compressed air to the combustion system.

The compressor comprises the fan and alternating stages of rotating blades and static vanes.



## Combustion

Fuel and air are mixed and burned within the combustion chamber to convert chemical energy of the fuel into thermal energy within the gas-stream prior to entry into the turbines.

The needs of the system depend greatly on the application (civil or military aerospace, marine or power generation). However there are many common themes of technology that span all sectors.

## Turbines

An increasingly detailed understanding of the turbine is necessary to produce more fuel efficient engines.

Turbines blades extract power from the hot, fast gases downstream of the combustor. They spin at around 12,500rpm and live in an environment 200°C hotter than their melting temperature - that’s like putting an ice cube inside an oven.

## LEADING TECHNOLOGY

### TRENT XWB
World's most efficient large aero engine

### MTU POWERPACKS
Among the most advanced in the rail industry, meeting all the latest EU regulations on emissions

### UT DESIGN SERIES
Global benchmark for offshore oil industry: wave-piercing hull to improve efficiency and reduce fuel consumption

## LEADING INNOVATION

### £1.2 BILLION
invested in research and development annually

### MORE PATENTS
filed annually than any other UK company

### 15,500
engineers

### 31
university technology partnerships


**Name:** Andrew Lees

**Position:** Engineering Graduate

**Educated in:** University of Cambridge, Devonport High School for Boys

**A levels:** Maths, Further Maths, Physics, Chemistry

**Qualifications:** Masters of Engineering

**Day to day work involves…** I work on a four month rotation so get to experience different areas of the business but I am currently working in Critical Part Lifing. I carry out stress analysis on the most important components in an engine, and based on my findings, the customer is told how long they can operate those parts before they need servicing or replacing.

**The best thing about my job is…** that I get given real problems and told to solve them. I am asked to do things that have not been done before. I get challenged to push the limits of what is possible.

**The thing I like least about my job is…** going to meetings where problems are talked about, but nothing is done (thankfully this is rare)!

**Other careers considered:** Maths Teacher, University Lecturer

**Name:** Amy Compton

**Position:** Commercial Graduate

**Educated in:** Aston University, Welbeck Defence Sixth Form College

**A-levels:** Maths, Physics, Electronics and Politics

**Qualifications:** BEng Mechanical Engineering

**My day to day work involves…** My graduate scheme takes me through the Aerospace business on 3 month rotations, where I support the work we do with our Suppliers, Partners and Customers. Commercial work is all about helping to maintain profits, minimise risk and develop our strategies, at every stage of our product's lifecycle. I can be doing this by managing ongoing contracts with our current Customers, or negotiating new relationships with our Partners to develop future products!

**Other experience or previous professions:** Royal Air Force Engineering Officer

**The best thing about my job is…** getting to represent and support the sale and development of technology I'm passionate about!

**The thing I like least about my job is…** the potential for Jet Lag!

## University of Cambridge

# 14. Institute of Astronomy

[www.ast.cam.ac.uk](http://www.ast.cam.ac.uk)

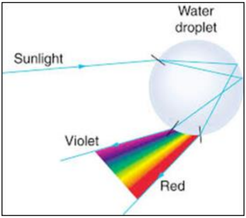
*The Eagle Nebula seen in visible (left) and infrared (right) light through the Hubble Space Telescope*

**Everything we know about the Universe beyond the confines of the Solar System comes from studying the light given off by cosmic objects.** Just by looking at the photons of light that happen to fall towards Earth we can learn about: the birth, life and death of other suns; the different kinds of exoplanets hurtling around their host stars; the formation and evolution of galaxies hundreds of millions of light-years away; and the distribution of matter on the largest scales of the cosmos.

## Spectroscopy

Light thus plays a crucial role in all astronomy and astrophysics research. Astronomers use telescopes both on the ground and in space not just to collect images of cosmic objects, but also to split the light detected into its constituent colours through spectroscopy. The spectrum of light given off by an astronomical object can reveal physical properties such as its temperature, density and pressure; it also allows us to deduce its distance from us, how fast it is moving, how much energy it is producing, and even its chemical composition.

The simplest form of spectroscopy you may be familiar with is when sunlight is dispersed naturally, through water droplets or a glass prism, to form a rainbow. Spectroscopes on modern telescopes are advanced instruments, but we shall be making a simple version using a CD: the grooves on the shiny side of the CD reflect different wavelengths (i.e. colours) of light at different angles to generate a spectrum.

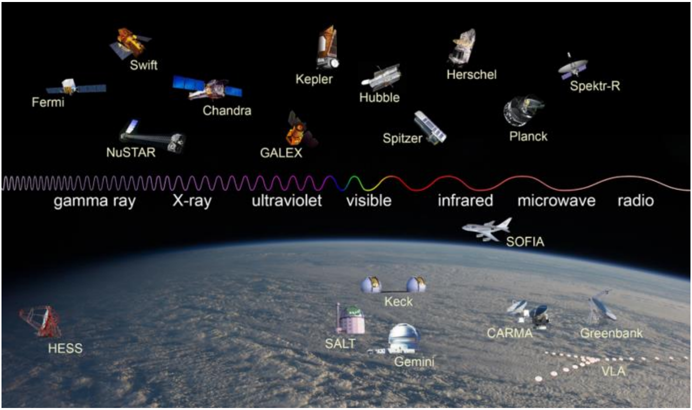



We can use this to show that different sources of light produce different kinds of spectra. Light given off by the Sun, a candle flame or an old-style (tungsten) light bulb will show a continuous spectrum containing a smooth distribution of all the rainbow colours.

Other light sources give off a very different spectrum. Atoms of different elements can emit bright lines only at very specific wavelengths, or colours. For instance, the light from a fluorescent light bulb shows bright violet, blue and green lines from atoms of the element mercury - scientists refer to these features as emission lines, and they can reveal what gases are present in space. Similarly, atoms of a particular element can also absorb light, leaving blank spaces, or dark lines known as absorption lines. Astronomers can use this information to figure out which elements are present in the outer layers of stars, as gas in the outer layers will absorb the light radiated from the core.

## All the colours of the spectrum

We are most familiar with the visible portion of the spectrum, where our eyes operate. But astronomers can only build up a complete picture of the Universe by collecting all the light available – from radio and infra-red through to ultra-violet and X-rays. Only then can we ‘see’ the light given off by the very coldest gas that fills the space between the stars, or the most explosive and violent regions of the cosmos, such as supernovae or the surroundings of accreting black holes. Much of the invisible spectrum of light is absorbed by the Earth’s atmosphere, so many of the telescopes have to be located out in space on orbiting satellites.




### Read more

2015 is the *International Year of Light* - [http://www.light2015.org](http://www.light2015.org)

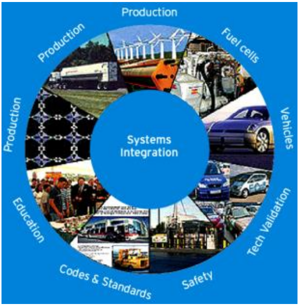
### Institute of Astronomy

The Institute of Astronomy (IoA) is a department of the University of Cambridge engaged in teaching and research in the fields of theoretical and observational Astronomy. A wide class of theoretical problems are studied, ranging from models of quasars and of the evolution of the universe, through theories of the formation and evolution of galaxies and stars, X-ray sources and black holes.

Much observational work centres on the use of large telescopes abroad and in space to study quasars, galaxies and the chemical constitution of stars. Instrumentation development is also an important area of activity, involving charge coupled devices and detector arrays for rapid recording of very faint light and the design and construction of novel spectrographs.

# 15. Arcola Energy

http://www.arcolaenergy.com



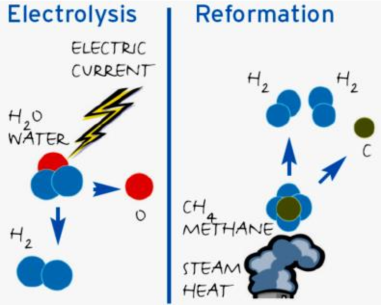

The "hydrogen economy" is a proposed system of delivering energy using hydrogen and fuel cells. The objective is to eliminate dependence on fossil fuels, using hydrogen as an energy carrier to combine a range of clean renewable energy generation technologies such as wind and solar power with clean power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

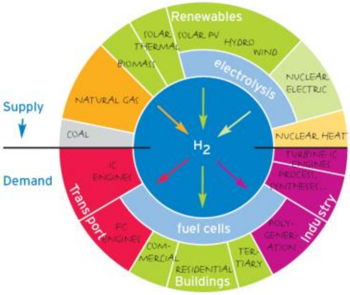
## This sounds too good to be true! What's the catch?

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.

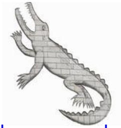
**The best thing about my job is...** being at the forefront of fuel cell technology and development within the UK.

**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.

## 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.

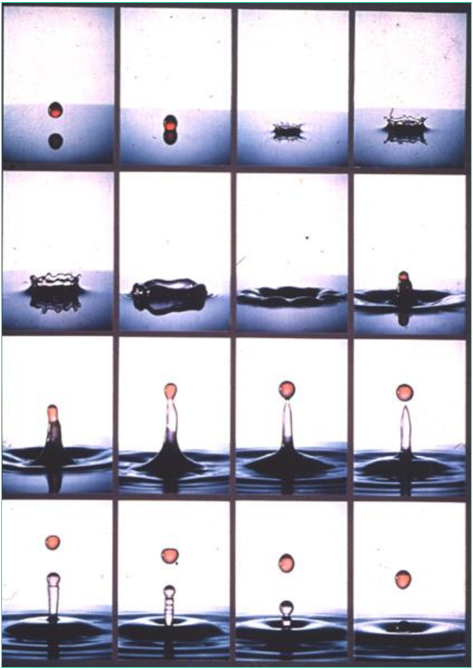
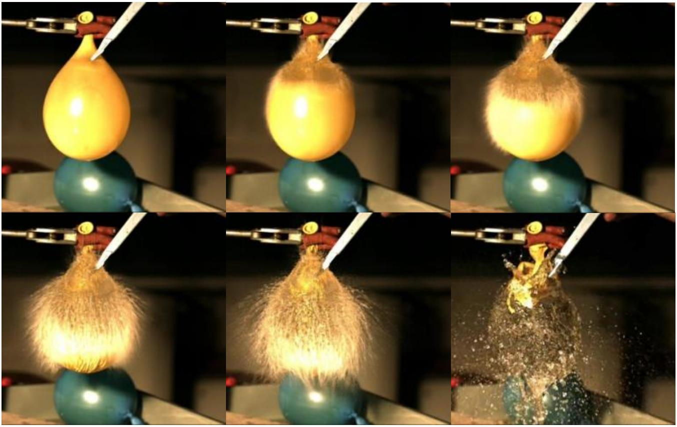


**Figure 1:** ➔ *A sequence showing a drop of red-dyed water falling into a pool of blue-dyed water.*

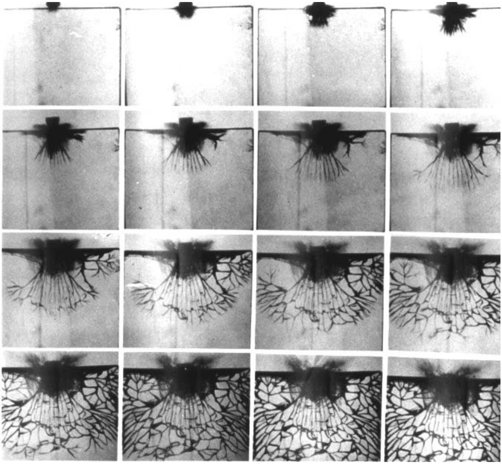
In the first frame the drop nears the surface. In the second, the impact has occurred and the drop has pushed the liquid aside producing a crown-shaped splash. In the following frames, the liquid rebounds and throws up a column or jet. Sitting on top of the column is the original drop of coloured water.



🡅 ***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

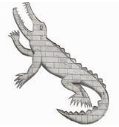
**My day to day work involves...** performing experiments and analysing data.

**Other experience or previous professions:** Day chemist

**The best thing about my job is…** the 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?

Biology is the science describing how life is built up of complex molecules, such as DNA or proteins, that make part of the cells constituting our body. Many famous physicists who are known for their achievements in traditional 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.

Despite these many contributions, physics and biology are still considered by most to be two different subjects. Physics is a discipline that is best defined by its approach: accurate measurements and coherent models to understand observations. Physics itself has two souls: on one hand a "reductionist" drive towards fundamental laws, which gave us Newtonian mechanics, optics, electricity and magnetism, and more recently quantum and particle physics; on the other hand the search for "universal" mechanisms, whereby some simple and system-specific rules give rise to macroscopic phenomena that are not present in the rules themselves. An example of the latter is a phase transition like boiling of water: this phenomenon is just "not there" if you look at the interaction forces between water molecules; other examples are traffic jams or people in crowds finding it hard to move about – these things happen but they are not coded in the rules that drivers and pedestrians give themselves. These systems are often called "complex systems".

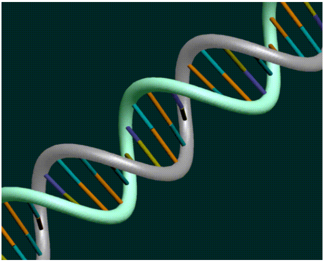
In biology, the rules are well known: molecules obey chemistry. But how these molecules and their reactions come together is phenomenally complex, even within a single cell, and we can make progress by developing the concepts that have been successful in other "complex systems". It is here that physics and biology currently have a really significant overlap, and important breakthroughs will be possible only by combining a deep knowledge of both areas. This approach is what we, in physics, call biological physics.

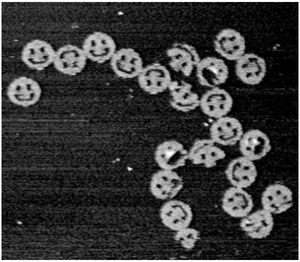
## DNA – a carrier of life and versatile building material for new applications

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 are 2 meters of it in each cell!

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.

In BSS we study the way DNA is arranged and moves within cell nuclei, and also use it to build “smart” nanomaterials, from molecular sensors to tiny DNA-origami nanopores that facilitate diffusion through cell membranes.



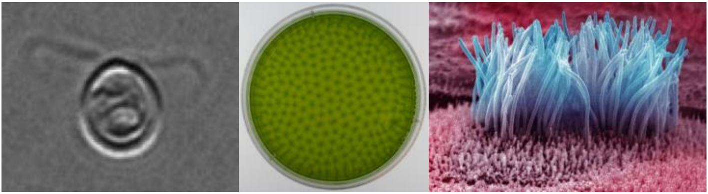


🡅 ***Figure 1:*** *DNA origami of viruses made by Paul W.K. Rothemund from a harmless virus-DNA. He "pinched" it into shape with "staples" made from much shorter DNA strands (ref.: P.W.K. Rohemund, Nature, Vol 440|16 March 2006|doi:10.1038/nature04586).*

## Beating cilia and swimming microorganisms

Many microorganisms have evolved to swim and find nutrients. Microalgae, such as phytoplankton in the ocean, swim by beating cilia. Cilia are microscopic filaments actuated by molecular motors (akin to those in muscle fibres). Cilia are also present in the human body, where they are involved in the transport of fluids, such as beating in unison to clear mucus from our lungs. The fluid environment of cilia is very different from the one we experience, e.g. in the swimming pool. On the scale of a cell, water is like treacle; viscous forces dominate over inertia, so reversible swimming strokes are no use (they land you where you started). Ciliated cells have evolved peculiar beating styles to efficiently propel through 'treacly' fluid, or pump it past them.

In the Cavendish Laboratory we study the experimental and theoretical biological physics of ciliary movement; from single cells to populations of swimming microalgae, and up to the tissues we have in our airways. Our research is inspired by current problems in medicine (diseases due to ciliary malfunction) and biotechnology (growing algae for carbon-fixing products and energy).



🡅 ***Figure 2*****:** *The swimming microalga Dunaliella moves by beating two cilia. The cell is also bottom-heavy, so its swimming is biased in flows by a combination of gravitational and viscous torques (gyrotaxis). Gyrotaxis gives rise to the beautiful patterns shown on the right (a top view of a Petri dish). It also causes the peculiar behaviour of suspensions of algae in pipes, which has relevance to culturing algae industrially in photobioreactors, where algae are grown in transparent pipes. (M. D. Haw & O. A. Croze, Physics World 25 39-43 (2012) http://iopscience.iop.org/pwa/full/pwa-pdf/25/02/phwv25i02a37.pdf). On the right is a touched-up image (from Boots website) of cilia in the lungs; these filaments beat at about 10Hz, and maintain a flow of mucus out of the lungs, serving as a barrier against bacteria and dust.*

## “Imaging” oxygen levels in diseased tissue

Our cells need oxygen to live and fulfil their functions. Oxygen is constantly supplied by our blood stream to both healthy and unhealthy cells. “Diseased” cells, such as those that are part of tumours, do not consume oxygen in the same way as healthy ones, or simply don’t benefit from the same efficient delivery. As a result, anomalous oxygen concentrations are found in tumours. Measuring oxygen levels in a non-invasive way is a very useful test to assess the stage of development of the disease and design more effective treatments for patients.

Using imaging techniques based on infrared light and nanoscopic probes, we develop imaging techniques in BSS to “see” oxygen concentrations within living tissue, without the need of invasive surgical procedures (http://bohndiek.bss.phy.cam.ac.uk/).

## University of Cambridge

# 18. 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'.

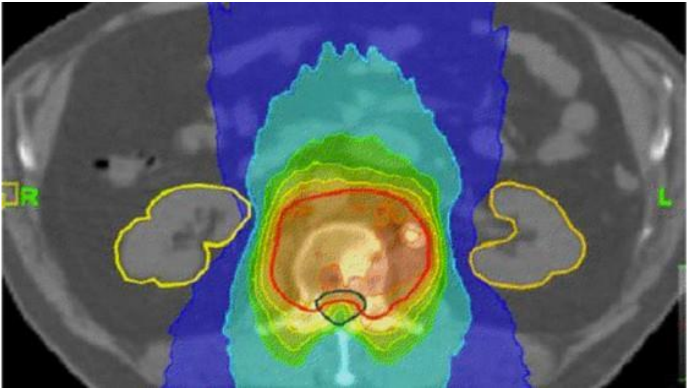
Today's radiotherapy uses high energy X-rays to destroy cancer cells. We have effective methods for delivering the radiotherapy to the target in order to kill the cancer cells. Side effects occur because some normal tissue always lies next to, or even within the edge of, the tumour. Better targeting 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)*

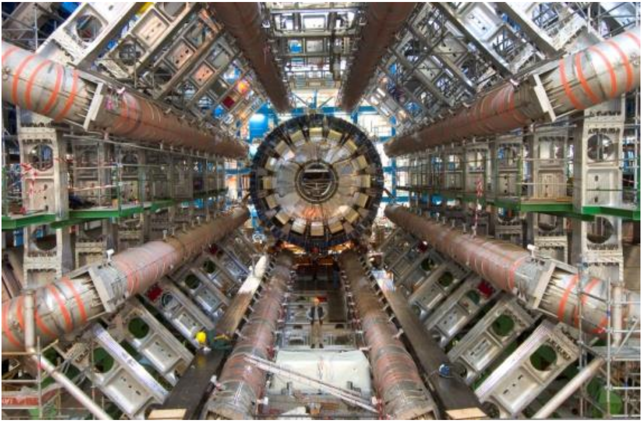



↑ ***Figure 2:*** *Image-guided intensity modulated RT plan for a patient with a spinal tumour. (Credit: N.Burnet)*

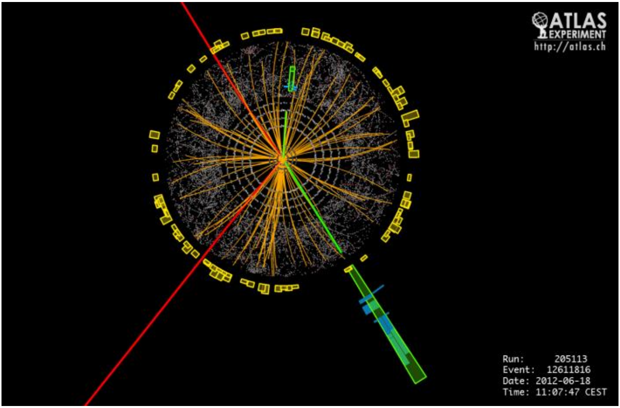
## What's the link between high energy physics and radiotherapy?

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 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.



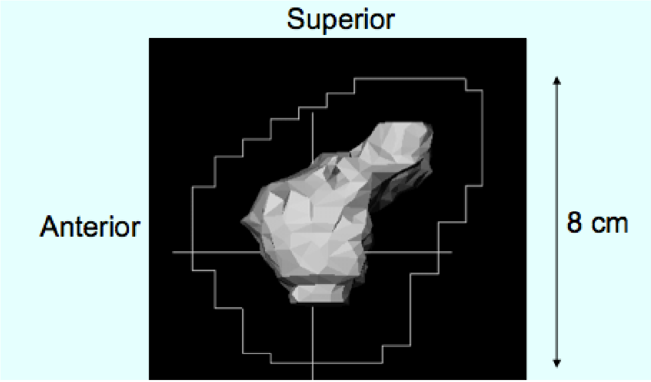
↑ ***Figure 3:*** *the ATLAS detector, at the Large Hadron Collider, CERN. (credit: CERN)*




🡅 ***Figure 4:*** *Example of an image of a candidate event (possibly 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

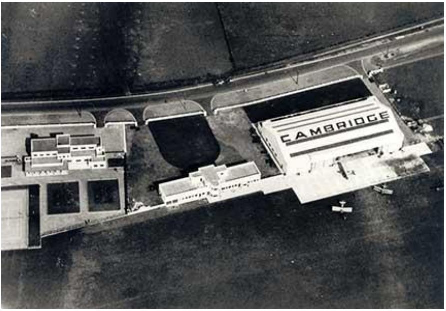
Physics in medicine pages:

http://www.insidestory.iop.org/

# 19. 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, as a chauffeur drive company in a small lock-up garage in Brunswick Gardens, Cambridge. 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.

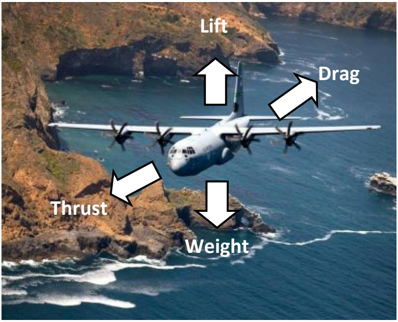
Marshall's company built, under subcontract, the famous droop nose for Concorde during the 1960's. During the 1980's Marshall's ties with the RAF were solidified by the conversion of C-130 Hercules to perform air to air refuelling in response to the Falklands Conflict, this vital modification was designed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

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. 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

# 20. 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, the detonation of an explosive gas, 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.

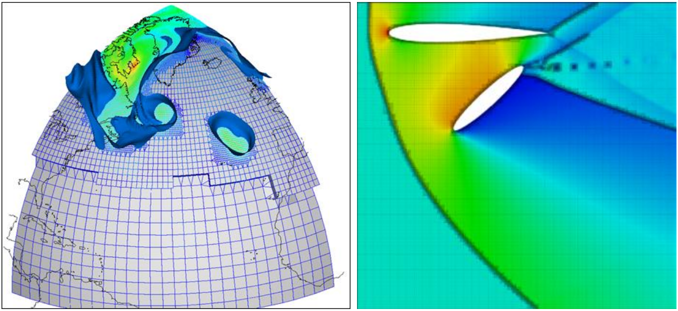


***Figure 1:*** *Left: part of a global atmospheric simulation. Right: supersonic flow over a payload dropped from an aerofoil, representing the wing of an aeroplane.*

## 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 in 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, *Figure 2* shows the predicted atomic structures of quartz at atmospheric pressure and at 10GPa (about 100,000 times atmospheric pressure).

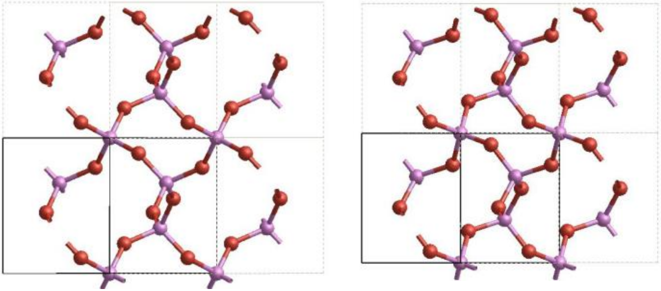


***Figure 2:*** *Repeating unit of quartz crystals at atmospheric pressure (left) and 10GPa (right)*

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

# PHYSICS AT WORK 2015

The Physics at Work Exhibition is a major annual event at the Cavendish Laboratory. The primary aim of this exhibition is to stimulate interest and encourage wider participation in physics amongst 14-16 year olds by showcasing the many and varied ways in which physics is used in the real world. This annual event is extremely popular with schools, with the 2300 available places for students fully booked within a couple of weeks of the invitations being sent out.

The Physics at Work 2015 Exhibition is an integral part of the Cavendish Laboratory's Educational Outreach Programme.

This booklet has been created to accompany the Physics at Work 2015 Exhibition. It is designed to introduce the exhibition and supplement the event by providing information to accompany each of the exhibits. The booklet can be used in many different ways, including:

- consolidation or extension of attendance at the 2015 Physics at Work Exhibition
- introductions to topics
- careers discussions
- extra material to support, encourage and challenge those students that complete curriculum work ahead of their peers

An on-line version of this booklet is available through the 2015 Physics at Work website at:

http://outreach.phy.cam.ac.uk/programme/physicsatwork

For more information about physics-based activities and events in the East of England please contact:

Educational Outreach Officer, Cavendish Laboratory, University of Cambridge, J J Thomson Avenue, Cambridge, CB3 0HE

Tel: 01223 333318 Fax: 01223 766360

E-mail: outreach@phy.cam.ac.uk

Or visit: http://outreach.phy.cam.ac.uk

Twitter: @physicsoutreach

Kindly supported and sponsored by

THE CAVENDISH LABORATORY

UNIVERSITY OF CAMBRIDGE

TTP

IOP Institute of Physics
East Anglia Branch

The MathWorks™
Accelerating the pace of engineering and science

EPSRC
Engineering and Physical Sciences Research Council