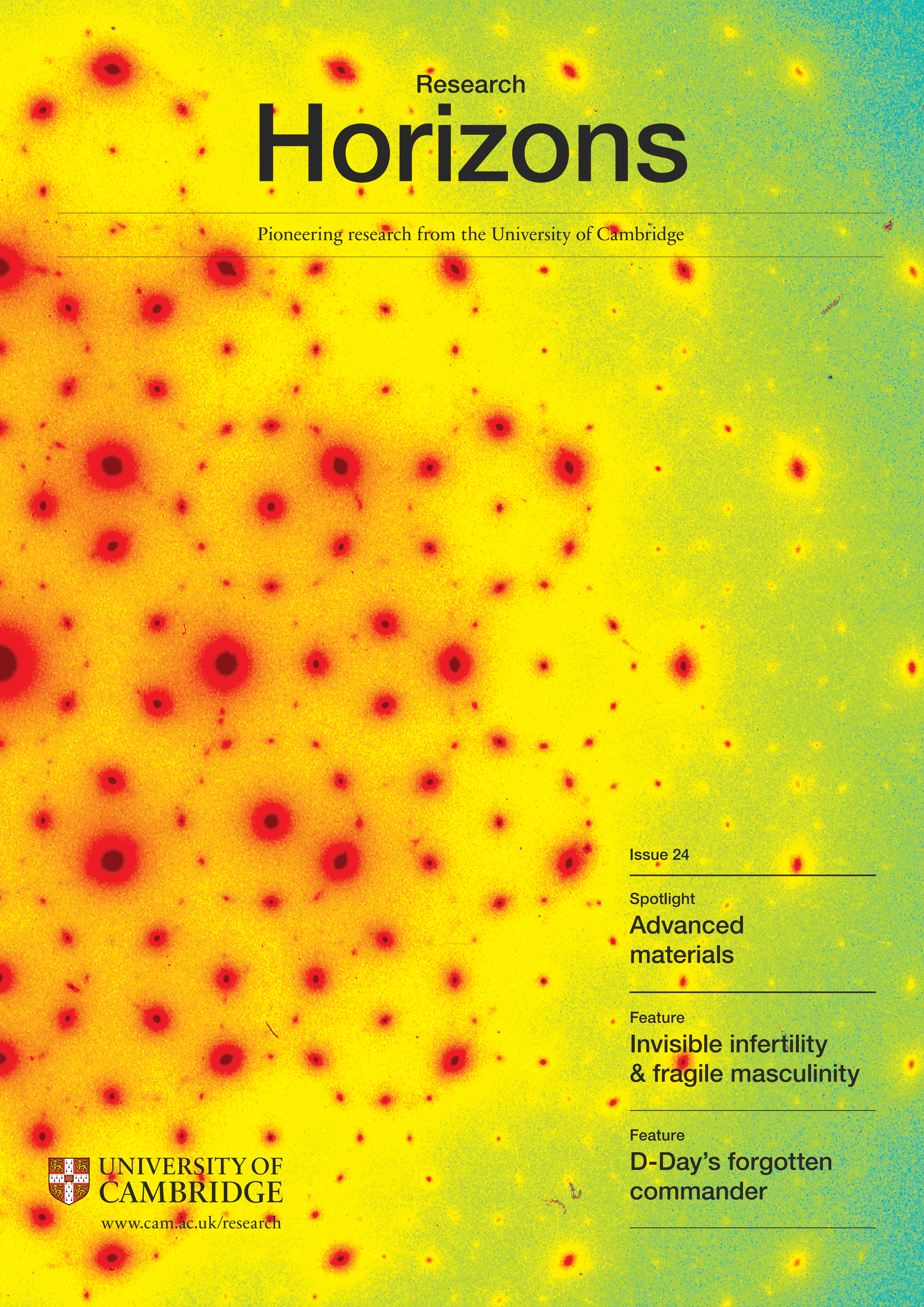

Research

Horizons

Pioneering research from the University of Cambridge

Issue 24

UNIVERSITY OF CAMBRIDGE
www.cam.ac.uk/research

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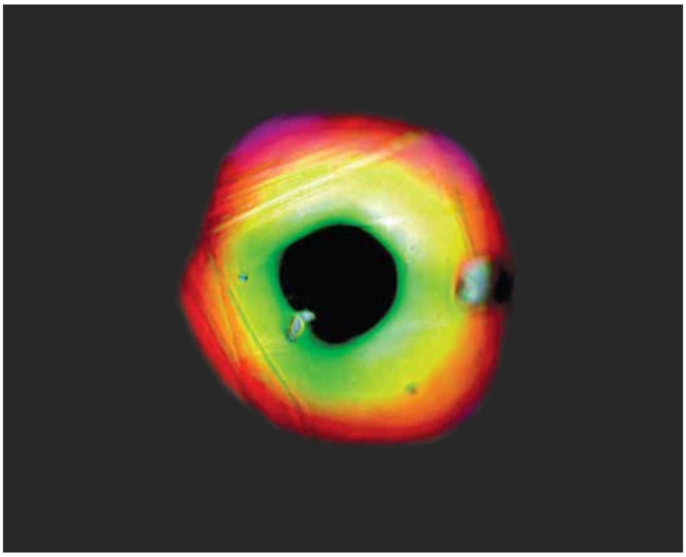

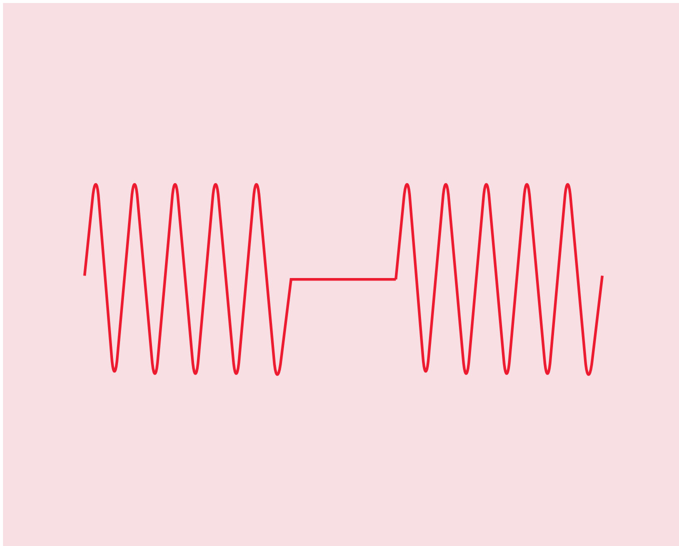

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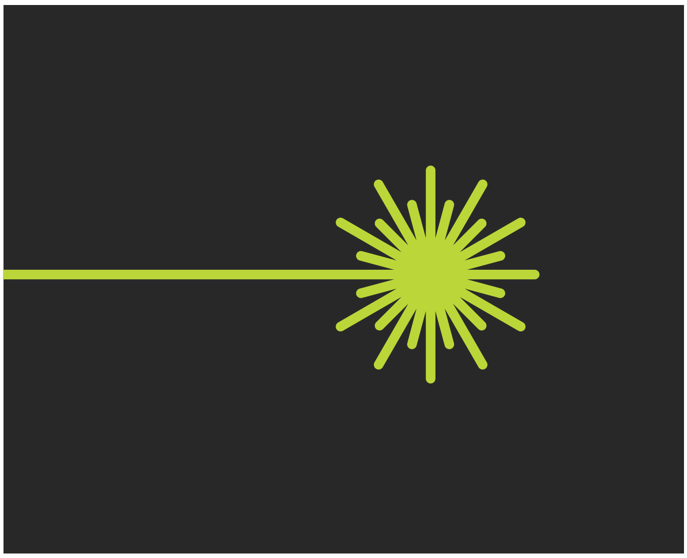
E Extreme sleepover



Welcome

Advanced materials have a lot to live up to: according to the UK government, they are one of the "eight great technologies which will propel the UK to future growth and help it stay ahead in the global race." With potential uses in applications like low-energy lighting and electrical wiring, advanced materials are an essential part of a future that is more energy efficient and less demanding of natural resources. They also underlie the technical wizardry that could give us mobile phones with in-built health diagnostics, windscreens with real-time information updates and even energy-generating clothes.

Broad applications they may be, but at the heart of each material lie step changes that are taking place in the engineering or processing of materials to be stronger, cheaper, lighter, more conductive – simply better. The field of advanced materials has long been a research strength in Cambridge, and we cover some of the new developments in this area in this issue. With recent large-scale investments in infrastructure, and doctoral training and research programmes, we aim to continue to design materials with radically altered functionality, and take these from discovery through to application.

Another area that depends on the production of new forms is synthetic biology. In this issue, we describe how a new open-access initiative in Cambridge plans to help synthetic biologists build new forms of plants to make food, fuel, chemicals and drugs.

Elsewhere, readers will find coverage of Bronze Age archaeology and Ireland's literary legacy, as well as two articles on reproductive health – research aimed at reducing the risk of stillbirth and a study uncovering the societal silence around male infertility.

Finally, we continue the Extreme Sleepover series, in which we hear about some of the experiences of our researchers in the pursuit of their studies. This issue, Earth Sciences PhD student Julia Gottschalk tells us about her mud-spattered trip aboard a "science factory" floating on the Atlantic Ocean.

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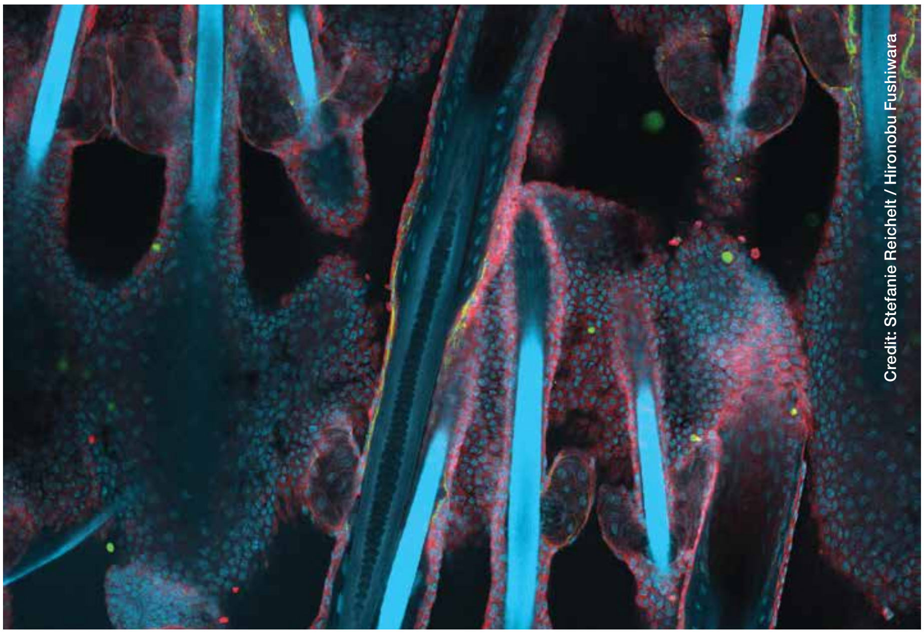
News



Picture this

Image
3D confocal image reconstruction of mouse skin

What links astronomers with oncologists, and chemists with art historians? "The desire to visualise and record what no one has seen before."

In today's digital world, an image can convey far more than a thousand words. Technological advances have made imaging a powerful tool, but until now there has been little sharing of expertise across disciplines.

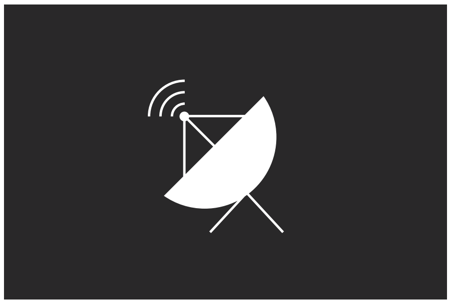
IMAGES, a recently launched network in Cambridge, is redressing this balance by encouraging the sharing of software and instrumentation developments, as well as of scientific ideas and proposals.

"We are connected by the desire to visualise and record what no one has seen before," said Dr Stefanie Reichelt, from CRUK Cambridge Institute. "Imaging has never been as exciting as it is now, with new technologies emerging all the time. The resolution limit in light microscopy, which had seemed unbreakable for 200 years, is now less than 100 nanometres with light. We can link imaging of whole organisms with molecular detail in real time."

The organisers view the multi-disciplinary approach of the IMAGES network – which currently spans 25 groups across the arts and sciences – as a vital forum for discovering and sharing new tools and new perspectives.

"As developers of image analysis and processing methods, we are keen to overcome limitations in imaging technologies that arise in applications," said Dr Carola-Bibiane Schönlieb (Department of Applied Mathematics and Theoretical Physics), co-organiser of the network with Reichelt and Professor Stella Panayotova (The Fitzwilliam Museum). "A continuous dialogue with applied imaging researchers is therefore essential to make advances in imaging research."

www.images.group.cam.ac.uk



Investment to open new frontiers in astronomy

A £119 million boost will help astronomers, including researchers in Cambridge, to unveil the mysteries of the origin and evolution of the Universe.

Vast networks of radio telescopes are being built in Australia and Africa that, together, will provide a 'collecting' area of over one square kilometre. When fully operational in 2028, the Square Kilometre Array (SKA) will be able to survey the sky 10,000 times faster than any radio telescope to date.

In March, the Science and Technology Facilities Council announced a major boost for the global project: £119 million for the UK's contribution of phase 1 of the instrument and to support the UK's leading role in designing the computing and software that will underpin the SKA.

As part of the UK involvement, researchers at Cambridge's Cavendish Laboratory, Department of Physics, are leading the Science Data Processor consortium and have a major role in the Low Frequency Aperture Array consortium.

The volume of data the SKA will produce is vast, amounting to around 20 times the current global traffic of the internet in its internal telecommunications system. In fact, to play back a single day's worth of SKA data on an MP3 player would take 2 million years. The University's High Performance Computing Service will help researchers test the scalability of architectures to the enormous proportions needed for the SKA.

www.skatelescope.org

News in brief

More information at www.cam.ac.uk/research

14.05.14
Cambridge has signed the Concordat on Openness on Animal Research in the UK, joining over 70 organisations.

06.05.14
An £8 million donation by the James Dyson Foundation will provide Cambridge's brightest engineers with some of the world's most advanced laboratories.

Roman rethink

Image
CGI view of the inner canal entrance

New archaeological discoveries will lead to a major rethink of one of the iconic Roman cities in the Mediterranean, say researchers.

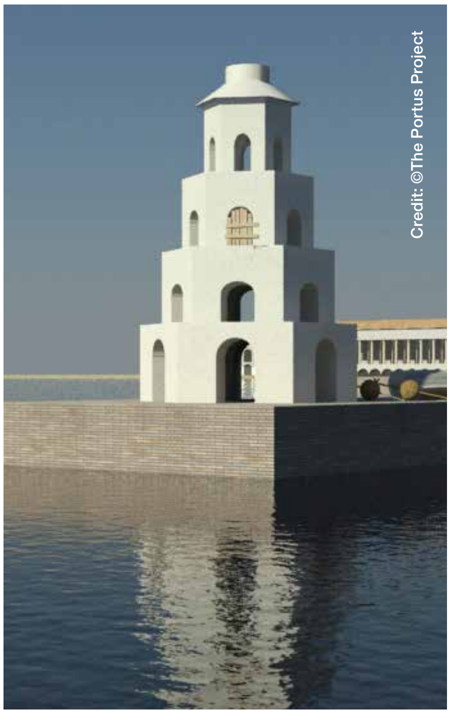
The harbours and port facilities at the great twin sites of Ostia and Portus, at the mouth of the river Tiber, linked Rome with its whole Empire in the first two centuries via a network of maritime routes forming the hub of the Empire's supply network.

For over a decade, researchers at the Universities of Southampton and Cambridge, with colleagues in Italy, have been unearthing the treasures of these sites 30 miles from Rome. Using state-of-the-art geophysical techniques and funded by the Arts and Humanities Research Council, the Portus Project has been gaining a fuller understanding of the site's development, as well as providing information that will help the Italian authorities manage this important area effectively.

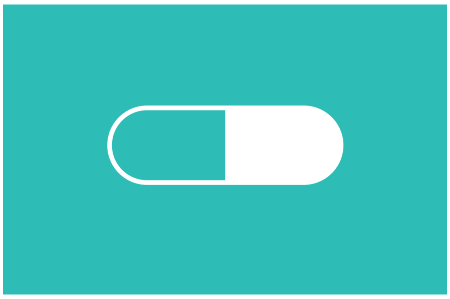
Now, a team led by Cambridge's Professor Martin Millett and Southampton's Professor Simon Keay has shown that Ostia is far larger than previously thought, stretching northwards beyond the Tiber. Moreover, the recent finding of warehouses, including one the size of a football pitch, along the northern bank of the river provides further evidence for the commercial activities that took place there.

"The results of our work completely transform our understanding of one of the key cities of the Roman Empire," said Millett, from the Faculty of Classics. "The enormous scale of the newly discovered warehouses will require a rethinking about the scale of commerce passing through the port."

www.portusproject.org



Credit: ©The Portus Project



NICE approves MS drug

A new drug based on decades of research at the University of Cambridge has been approved for use in people with relapsing-remitting multiple sclerosis (MS).

Clinical trials have shown that Alemtuzumab, marketed under the name Lemtrada, reduces MS activity, limits the accumulation of further disability over time and may even allow some existing damage to recover. The decision by the National Institute for Health and Care Excellence (NICE) brings to a conclusion work involving several research groups in Cambridge, stretching back over decades.

Professor Alastair Compston, Head of Cambridge's Department of Clinical Neurosciences, said: "I am delighted that the decision from NICE will make Lemtrada available on the NHS. [It] now provides an opportunity for neurologists to offer a highly effective therapy for patients with MS early in the course of their illness."

Lemtrada, manufactured by pharmaceutical company Genzyme, began life as Campath-1H, a drug developed out of research by Professor Herman Waldmann and colleagues in the Department of Pathology in the late 1970s as an immunosuppressant to prevent the rejection of bone marrow. However, the story of Campath stretches even further back, to research by Nobel-Prize-winning Dr César Milstein at Cambridge's MRC Laboratory of Molecular Biology in 1975 on monoclonal antibodies.

Compston identified Campath-1H as a potential treatment for MS in the late 1980s. The first MS patient was treated with the drug in 1991 and, as evidence began to mount that the drug would be effective if used to treat people before the disease process had progressed too far, Compston and his colleague Dr Alasdair Coles expanded the trials. The results of phase III clinical studies, published in 2012, confirmed that the drug is effective both in MS patients who are previously untreated ('first-line' therapy) and those who have already failed another treatment.

01.05.14

The government has approved a £165 million deal for Papworth Hospital to move to the Cambridge Biomedical Campus.

28.03.14

Cambridge has been awarded EPSRC funding for two new doctoral training centres in sensing and analysis.

26.02.14

Research growing 'mini-livers' from adult mouse stem cells has won the NC3Rs prize for reducing animal use in science.

From foundry to factory
building synthetic plants

Synthetic biologists choose a 'chassis' and then bolt on standard parts to build something that's tailor-made

Images
Marchantia – a primitive plant form used as the 'chassis' for designing new plants

A movement is under way that will fast-forward the design of new plant traits. It takes inspiration from engineering and the software industry, and is being underpinned in Cambridge and Norwich by an initiative called OpenPlant.

Humans have been modifying plants for millennia, domesticating wild species and creating a bewildering array of crops. Modern agriculture allows global cultivation of plants at extremely low cost, with production on the gigatonne scale of a wide range of biostuffs – from fibres, wood, oils and sugar, to fine chemicals, drugs and food.

But, in the 21st century, we face both ever-increasing demand and the need to shift towards more sustainable production systems. Can we build new plants that make better materials, act as miniature 'factories' for food and fuel, and minimise the human impact on the environment?

With this in mind, synthetic biologists are beginning to build new organisms – or at least reprogramme existing organisms – by turning the biology lab into an engineering foundry.

Synthetic biologists choose a 'chassis' and then bolt on standard parts – such as genes, the promoters that activate them and the systems they drive – to build something that's tailor-made. And, like open-source software programmers, they have been looking to open-access and the sharing of code – in this case the DNA that codes for each part – as a practical means of speeding up innovation.

"Providing free access to an inventory of molecular parts for use in the construction of diverse plant-based systems promotes their creative use by others, just as the open-source feature has driven innovation in the computer software industry," explained Professor Sir David Baulcombe from Cambridge's Department of Plant Sciences.

Earlier this year, the University of Cambridge and the John Innes Centre in Norwich received £12 million in funding for a new UK synthetic biology centre – OpenPlant – to focus on the development of open technologies in plant synthetic biology and their application in engineering new crop traits. The effort is being led by Baulcombe and Dr Jim Haseloff in Cambridge, and by Professors Dale Sanders and Anne Osbourn in Norwich.

It's one of three new UK centres for synthetic biology that, over the next five years, will receive more than £40 million in funding from the Biotechnology and Biological Sciences Research Council

and the Engineering and Physical Sciences Research Council.

OpenPlant aims to establish the first UK open-source DNA registry for sharing specific plant parts. It will also support fundamental science: "Construction of these parts will allow us to test our understanding of natural plant systems in which assemblages of parts create a greater whole," Baulcombe explained.

Researchers like Baulcombe and Haseloff, who also leads a new Strategic Research Initiative to advance cross-disciplinary research in synthetic biology in Cambridge, believe that the investment in the three new centres will help the UK stay at the leading edge of plant synthetic biology.

"Any large-scale reprogramming of living systems requires access to a large number

Left to right
Dr Jim Haseloff
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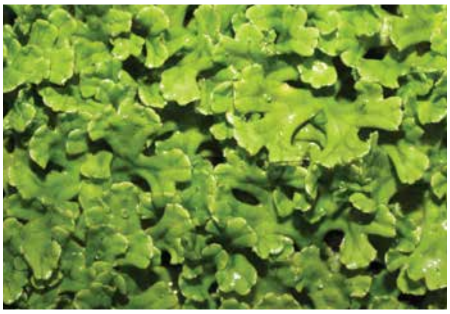
Credit: All images, Jim Haseloff



of components and, as the number of these parts balloons, the cost of building a portfolio of patents, or licensing parts from patent owners, could strangle the industry and restrict innovation," explained Haseloff.

"While US researchers lead in the synthetic biology of microbes, the UK has the edge in plants. The field needs a new two-tier system for intellectual property so that new tools including DNA components are freely shared, while investment in applications can be protected."

As well as new DNA components, Haseloff and colleagues have been focusing on a new plant chassis. Rather like the frame of a car, the chassis is the body of the cell that houses the rest of the desired parts. And for this they have turned to liverworts, relics of the first land plants to evolve around 500 million years ago.

The *Marchantia polymorpha* liverwort is small, grows rapidly, has a simple genetic architecture and is proving such a useful test-bed for developing new DNA circuits that Haseloff has launched a web-based resource (www.marchantia.org) for a growing international community to exchange ideas. The hub characterises one of the wider aims of OpenPlant in promoting interdisciplinary exchange between fundamental and applied sciences, and is one of a series of collaborative projects, such as OpenLabTools (see panel), which are promoting open technology, innovation and exchange between engineers and physical, biological and social scientists across the University.

In parallel with the development of standardised parts, the Centre will support around 20 researchers and their teams in Cambridge and Norwich who are engineering new plant traits. For instance, scientists at the John Innes Centre are investigating new systems for producing useful compounds like vaccines. In Cambridge, researchers are creating systems with altered photosynthetic capabilities and leaf structure to boost conversion of the sun's energy into food, as well as developing plant-based photovoltaics for fuel.

Another of OpenPlant's aims is to foster debate on the wider implications of the technology at local and global scales. As Baulcombe described, "The open source feature may allow straightforward discussion about the applications of synthetic biology in plants. Societal discussion about other strands of biotechnology has been greatly hampered by the complications following from intellectual property restrictions."

"We think that biological technologies are the underpinning of the 21st-century's industrial processes," added Haseloff. "Plants are cheap and inherently sustainable, and have a major role to play in our future. In order to implement ideas and shift towards more rational design principles to support advances, we need to have the ability to exploit synthetic biology technologies in a responsive way, and that's where we see OpenPlant contributing in the years to come."

www.openplant.org

OpenLabTools

OpenPlant is part of a wider move towards 'sharing' in Cambridge that now includes scientific tools of the trade.

Resourcing laboratories with scientific tools is a costly business. An automated microscope, for instance, could cost upwards of £75,000, and yet be a key tool in materials and biological laboratories.

Now, an initiative coordinated by Dr Alexandre Kabla, from the Department of Engineering, is rethinking how scientists can access the tools that they need at a less-prohibitive cost.

He recognised that a wealth of instrument-building know-how exists across the University – expertise that could be drawn on to develop a suite of low-cost open-access scientific tools.

Raspberry Pi, for example, was conceived and incubated in the Computer Laboratory to encourage children to learn programming for themselves: this credit-card-sized computer is now available for only $25.

The OpenLabTools initiative has set itself the task of creating high-end tools such as microscopes, 3D printers, rigs for automation and sensors, with an emphasis on undergraduate and graduate teaching and research. It was created with funding from the University and the Raspberry Pi Foundation, and is supported by an academic team of engineers, physicists, materials scientists, plant biologists and computer scientists.

"Current projects primarily focus on the development of core components, thanks to the contributions of a team of physics and engineering students. However, we have already made significant progress towards the development of imaging systems and mechanical testing devices," said Kabla, whose own expertise lies in the physics and mechanics of biological systems. "We anticipate that these will be rolled out in undergraduate laboratories sometime next year."

To encourage open access, 'How To' manuals and designs are being published on the OpenLabTools website.

"It's an exciting prospect," said Kabla. "When you consider that consumer-grade low-cost microscopes are essentially a digital camera with a high magnification objective, not only can we build this but we can also provide a means to automate the microscopy, dramatically reducing the cost of the tool. The blueprints and tutorials we make available will be useful for undergraduate and research projects, as well as school activities and small-scale industrial applications running on a tight budget."

www.openlabtools.org

Invisible infertility & fragile masculinity

Male infertility is as prevalent as female infertility but it's invisible in our society, finds new research.

The day before the artificial insemination, Dr Liberty Barnes' husband came down with flu, killing his sperm. The medical staff assured him – incorrectly – that the fever didn't kill his sperm, that it was a 'fluke', and that his wife's infertility – the reason for the appointment – could be overcome, even though a scan had revealed her ovaries to contain healthy eggs.

"My husband's sperm was dead and I had a live egg in the queue, yet infertility was still my problem. If dead sperm doesn't qualify as infertility, what does?"

For Barnes, a medical sociologist now based at the University's Department of Sociology, the experience raised questions. While she could find dozens of highly regarded books on women, when it came to infertility, men were missing – despite infertility being equally as common in both sexes.

Intrigued, she tried to find out more. "Initially, it seemed very strange: I couldn't find the doctors, I couldn't find any patients or figure out what the medical conditions were. It was an information black hole."

Once some clinics were tracked down, research began in earnest. Barnes spent over 100 hours shadowing doctors in five clinics in different states across the USA, as well as interviewing many of the couples involved (men and women separately). The work forms the basis of a new book, *Conceiving Masculinity*.

During the research, she found a "culturally sanctioned suppression of dialogue around male infertility."

Even though male infertility is responsible for half of all cases of infertile couples, "decades of misogynistic limelight on infertile women has left a 'categorical hole' in medical systems, with very few male infertility specialists and no official board certification for practitioners in the US," she said.

Some men seeking treatment end up further damaged by malpractice – having been prescribed testosterone, for example, which arrests sperm production; often this is the result of them receiving treatment by specialists in the wrong areas, such as a general urologist or their wife's doctor.

And those that do manage to engage with male infertility specialists are often fed information about their disorder through metaphors that mask infertility – frequently involving traditional male activities such as plumbing, sport or car mechanics – to the point where two thirds of infertile men interviewed for the study simply didn't consider themselves infertile.

"This is not some kind of deep-seated denial on the part of these men. There is an entire culture and medical system that makes it possible for men to be infertile and not even realise it," said Barnes, a member of the Reproductive Sociology Research Group led by Professor Sarah Franklin. "Male infertility is as prevalent as female infertility, but it's invisible in our society."

Most cases of male infertility are referred to IVF clinics – a process in which women bear the brunt. For many, male infertility is repaired in female bodies."

Most infertile men, even those who do self-identify as infertile, are able to 'intellectually reframe' their infertility issues as a medical condition somehow separate from their self, explained Barnes.

"This separation of body and self, while rare in female infertility, is the standard coping mechanism in men – that their

> "There is an entire culture and medical system that makes it possible for men to be infertile and not even realise it"

'messed-up plumbing' is not their fault and in most cases repairable. Many men cling to the notion that if you have a problem that can be fixed, you don't have a problem. Instead of telling these men they're infertile, you hear doctors saying 'oh, it's just an issue with your blocked exhaust.'

"The doctors actually provide men with the linguistic strategies to separate body from self."

Culturally, male fertility is intrinsically bound up with ideas of virility, machismo and sexual potency because it hinges on that very essence of manliness – semen. As William, a businessman in his late thirties interviewed for the research, puts it: "Men should be able to gush sperm all over the place."

For Barnes, the prevarication around male infertility is symptomatic of widespread cultural nervousness to expose masculinity as in any way fragile: "Masculinity is equated with power; protecting and expressing power is a key function of societies and states." In the book, she cites the global media panic around a 1992 study showing sperm counts were dropping.

Male infertility hits masculine identities – from the personal to the national – right where it counts, says Barnes. One interviewee described his desire for fatherhood as "kind of the only purpose of life." Another said his infertility led him to "doubt the toughness" of his penis.

Consequently, once a man is diagnosed, almost as much effort is taken to alleviate this perceived trauma to masculinity socially as is taken to treat it medically. When interviewed, doctors reeled out a progressive rhetoric. But in the infertility clinics, Barnes found a culture designed to enforce gender stereotypes and bolster masculinity.

"Every doctor I spoke to and medical seminar I went to, I heard time and again: we've got to help society move past archaic ideas that reproduction is women's work. Then when I was in the clinics, it was complete immersion in traditional gender ideology: penis jokes, talk of balls – everything was power and virility."

Diagnoses were shrouded in metaphors invoking factories/bridges/engines – technological achievement hiding biological failure. One doctor who Barnes shadowed, when prescribing hormone treatment to boost testosterone, would tell patients that side effects include "the urge to hit a ball really hard or drive really fast." Barnes describes this claim as scientifically debatable.

The assumed functionality of male sexual biology also translated to the first experience of the clinic – the collection cup. Men describe being pushed into a room or even just behind a curtain with no instruction beyond "fasten the lid tightly."

Medical institutions assume men can masturbate under any conditions, will enjoy it, and be able to shoot semen straight into a cup, says Barnes. Some interviewees told her the semen they provided was both of particularly poor quality and limited due to stress and the amount they were able to catch. In fact, most men found this confusing and uncomfortable – especially when confronted with the choice of 'performing' or extraction by needle from the testicle.

Barnes found the extraordinary lack of medical professionals specialising in male infertility as opposed to those in female infertility to be part of a damaging cycle: "When I spoke to organisations about this hole in the system, they would tell me it's because it's not needed. Men aren't coming forward for treatment, so there appears to be little demand. But then those that do come forward, struggle to find help, which – combined with the social stigma – means that many give up."

There is a medical and social price to pay, she says. Research into male infertility is not as advanced as that for female infertility. And societal silence on the subject means men who want and may well be able to have children if treated are not.

The cultural invisibility of infertile men is inherently conflicting, says Barnes. On the one hand, male infertility doctors complain about the lack of attention the topic receives. But on the other, they realise this invisibility protects men and masculinity by suppressing the issue.

"If you promote male infertility as a label to encourage more men to come forward for treatment, you will have a harder time helping them pretend they're not actually infertile."

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Beyond the blood of Clontarf

Fresh analysis of the literary portrait of the Battle of Clontarf – a decisive battle fought a thousand years ago in Ireland – offers a glimpse of a thriving intellectual culture in the generations that followed.

The Vikings were back in Dublin at Easter, marching through the streets, screaming murderous battle cries, and demanding beer from the locals as if the last thousand years had never happened. The occasion was a re-enactment of the Battle of Clontarf, a pivotal struggle in Irish history which was fought on Good Friday, 23 April, 1014. For its millennium, some 500 costumed enthusiasts, dressed as either Viking invaders or Irish warriors, met in St Anne's Park to reconstruct the bloody encounter. Another 40,000 spectators turned up to watch.

Until the anniversary of the Battle of Hastings in 2066, this rematch is likely to stay on record as the biggest millennial reconstruction the world has ever seen. "For our lifetime this is it," Barry Gaynor, from the Fingal Living History Society, enthused to the *Irish Times.* "This," he added, "is the big one."

In Ireland, children are still raised on the story of the Battle of Clontarf, and many of this year's anniversary activities follow the popular narrative. This styles the battle as a quasi-nationalistic, blood-soaked clash, between the army of Brian Boru, the Irish High King who died at Clontarf, and an allied force led by the rebel king of the territory of Leinster, Máel Mórda, and Sitric, of the Dublin-based Vikings. Frequently, it is depicted as an Irish victory, which, with Brian's death, came at a high price. Recently, a Dublin-based historian has even asked whether Clontarf is "a medieval version of 1916" – likening it to the Easter uprising, in which a later generation of Irishmen were martyred in the national cause.

Image
Battle of Clontarf
by Hugh Frazer (1826)

> Re-enactments aside … Clontarf remains a significant but mysterious moment in Ireland's past, defined by an account which is as unreliable as it is popular

Equally, researchers have long pointed out that the reality was more complex. For example, both Irish and Vikings clearly fought on both sides at Clontarf, while the outcome – which seems something of a gory stalemate – is just as doubtful as its nationalistic connotations. The debate is not helped by scarce evidence from the battle itself. No archaeological remains have survived and we still don't know exactly where the battlefield was. Contemporary records offer little more than a date and a list of the dead; otherwise, we are reliant on later, more suspect accounts.

Of these, the most influential is called *Cogadh Gáedhel re Gallaibh (The War of the Irish Against the Foreigners)*, a remarkable work which is the subject of a new study by Dr Máire Ní Mhaonaigh, from the Department of Anglo-Saxon, Norse and Celtic. Written about 100 years after the date of the battle, it was probably commissioned by Brian's great-grandson, Muirchertach, who was then the most powerful king in Ireland. Academics are rightly suspicious of its depiction of Clontarf, seeing it as skilful propaganda.

Ní Mhaonaigh's research, however, shows *Cogadh* to be something more – not merely a partisan propaganda piece, but a brilliant work of art. "It is in this text that Brian's image was cultivated, and our perception of Clontarf owes much to its learned author's pen," she said. "Whatever the precise nature of the battle, its cultivation as literary history tells another, very important story."

Unfortunately for the re-enactment enthusiasts, this also makes it an even less credible account of what happened. In fact, part of the depiction of the battle appears to have been based on an earlier work about the siege of Troy. During a powerful, rousing passage, the unknown author of *Cogadh* likens Brian's son, Murchad, to the Trojan hero, Hector. Murchad led Brian's army at Clontarf (Brian himself was probably in his 70s at the time), and the author casts him as "the last man who had true valour in Ireland."

Close reading of this Hector comparison reveals that it drew in a sophisticated manner on an Irish translation of a 5th-century, Latin account of Troy by Dares Phrygius called *De excidio Troiae historia*, which became a staple basis of medieval scholarly fascination with the Trojan war. Tellingly, this Irish version – *Togail Troí* – also appears in the very same manuscript in which the earliest (albeit fragmentary) version of the *Cogadh* is found. It is hardly a leap to suggest that, given the similarities, whoever wrote the story of Clontarf had it to hand.

Yet while this makes the conventional story of Clontarf more literary history than historical fact, the document itself is a masterpiece. Through it, we catch sight of a vision of medieval Irish culture which, by the 12th century, was achieving standards that rivalled anything being produced in continental Europe at the time.

Whoever wrote *Cogadh* was highly sophisticated, and deeply learned. Far from merely comparing Murchad to Hector, the author places the Irish leader at the end of a list of six great-warrior heroes, starting with Hector himself. This consciously imitates the idea of a world with six "ages" represented by six different stages of human life, from infancy, through to old age. The concept, which dates back to the 5th century, suggests that world history is one of gradual decline after a golden youth. It was a recurring motif in the culture of medieval Europe, appearing, for example, in the work of Bede and the stained glass windows of Canterbury Cathedral.

Cogadh's author, however, did something completely new, incarnating the six ages with six heroes, through whom we trace the progressive descent of valour. He even calculated this mathematically: seven of each hero are required to match the ability of his predecessor on the list, according to which it would have taken 16,807 Murchads to match a single Hector. Murchad is the last, great hero the world will ever see, the author suggests, adding, rather despondently, that "it will be a palsied, drivelling dotard ever after."

Such remarkable, creative scholarship was, Ní Mhaonaigh argues, the achievement "of a consummate craftsman with a particular tale to tell." More than a copy of *Togail Troí*, it would have demanded extensive learning, and access to wide-ranging cultural knowledge and resources.

So where does it leave Clontarf, Murchad and Brian? Ní Mhaonaigh stresses that their legacy was, in part, *Cogadh* itself. "This was the work of a sophisticated and learned author," she added, "skilfully weaving a cloth of his own design reflecting motifs and patterns from his entire scholarly wardrobe."

Re-enactments aside, then, Clontarf remains a significant but mysterious moment in Ireland's past, defined by an account which is as unreliable as it is popular. Yet at the same time, *Cogadh* offers a glimpse into the vibrant intellectual world of the generations that followed. If its trustworthiness is in doubt, its value as a work of literature seems beyond question. Perhaps sensibly, however, nobody has yet raised this rather subtle distinction with the latest horde of Dublin Vikings.

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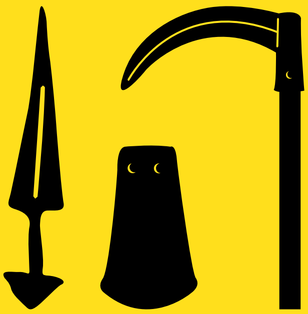
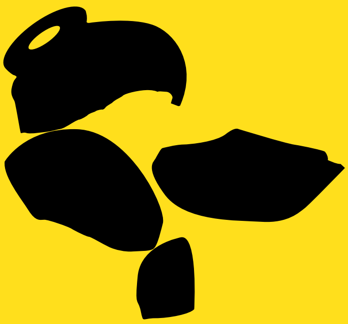
Whatever happened to the Harappans?



? Exhausted their resource base

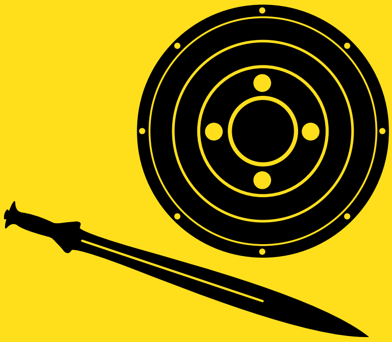
? Population increased

? Glacier-fed rivers changed their course



? Trading economy broke down

? Climate change



? Succumbed to invasion and conflict

The Harappan Civilisation of ancient Pakistan and India flourished 5,000 years ago, but a thousand years later their cities were abandoned. Researchers are piecing together what could have happened to this sophisticated Bronze Age society of master builders and master craftsmen.

Often regarded as 'faceless', the Harappan or Indus Civilisation was a society who built 'megacities' and traded internationally in luxury craft products, and yet seemed to have left almost no depictions of themselves.

But their lack of self-imagery – at a time when the Egyptians were carving and painting representations of themselves all over their temples – is only part of the mystery that surrounds the people of the Indus Civilisation.

Indus cities – like Harappa in present-day Pakistan and Rakhigarhi in India – flourished in the mid-to-late third millennium BC. However, by the start of the second millennium BC, their great urban centres had dramatically reduced in size or been completely abandoned.

Now, researchers from Cambridge's Department of Archaeology and Anthropology and Department of Earth Sciences have provided the first evidence that a widespread weakening of the Indian summer monsoon, causing long-term drought in north-west India around 4,100 years ago, was likely to have been a factor in this process.

Intriguingly, the finding links the onset of the decline of the Indus cities to a documented global-scale climate event, which also had an impact on Old Kingdom Egypt, the Early Bronze Age civilisations of Greece and Crete, and the Akkadian Empire in Mesopotamia.

"There is plenty of archaeological evidence from the five known large or 'megacities' that have been found over the past century to tell us about the rise of the Indus Civilisation, but relatively little about

It has long been suggested that other great Bronze Age civilisations also declined at a similar time, with a global-scale climate event being seen as the cause

its fall," explained archaeologist Dr Cameron Petrie. "As populations increased, cities were built that had great baths, craft workshops, palaces and halls laid out in distinct sectors, and these centres covered a total area roughly the size of 100 football pitches. Houses were arranged in blocks, with wide main streets and narrow alleyways, and many had their own wells and drainage systems. It was very much a 'thriving' civilisation."

Then around 2100 BC, a transformation began. Occupation in the cities seemed to have increased, then streets went uncleaned, buildings started to be abandoned, and ritual structures fell out of use. After their final demise, a millennium passed before really large-scale cities appeared once more in South Asia, some of which went on to become capitals of the great Ganges Kingdoms.

Some have claimed that major glacier-fed rivers changed their course, dramatically affecting the water supply and agriculture; or that the cities could not cope with an increasing population, they exhausted their resource base, the trading economy broke down or they succumbed to invasion and conflict; and yet others that climate change caused an environmental change that affected food and water provision.

"It is unlikely that there was a single cause for the decline of the civilisation. But the fact is, until now, we have had little solid evidence from the area for most of the key elements," said Petrie. "A lot of the archaeological debate has really only been well-argued speculation."

For the past seven years, Petrie has co-led a project to understand what happened to the Harappans with Dr Ravindanath Singh of Banaras Hindu University in India, investigating the archaeology, river systems and palaeoclimate of north-west India.

Funded primarily by the British Council UK–India Education and Research Initiative, and also by the British Academy, Natural Environment Research Council, Isaac Newton Trust and McDonald Institute for Archaeological Research, the multidisciplinary project involves archaeologists, earth scientists and geographers in Cambridge working together with researchers at Imperial College London, the University of Oxford, the Indian Institute of Technology Kanpur and the Uttar Pradesh State Archaeology Department.

Almost immediately after the project's beginning in 2008, the field reconnaissance team discovered that many of the archaeological sites were not where they were supposed to be, completely altering understanding of the way that this region was inhabited in the past.

When they carried out a village-to-village survey of how the larger area was settled in relation to sources of water, they found errors in the published geographic locations of ancient settlements ranging from several hundred metres to many kilometres. They realised that any attempts to use the existing data were likely to be fundamentally flawed. Over the course of several seasons of fieldwork they carried out new surveys, finding in consecutive years an astonishing 73 and 125 settlement sites that were previously unknown.

Now, research published in the journal *Geology* by former Gates scholar Dr Yama Dixit and Professor David Hodell, both from the Department of Earth Sciences, and Petrie has provided the first definitive evidence for climate change affecting the plains of north-western India, where hundreds of Indus sites are known to have been situated.

The researchers collected *Melanoides tuberculata* snail shells from the sediments of an ancient lake in Haryana and used geochemical analysis as a means of tracing the climate history of the region. "As today, the major source of water into the lake throughout the Holocene is likely to have been the summer monsoon," said Dixit. "But we have observed that there was an abrupt change about 4,100 years ago, when the amount of evaporation from the lake exceeded the rainfall – indicative of a drought."

Hodell added: "We estimate that the weakening of the Indian summer monsoon climate lasted about 200 years before recovering to the previous conditions, which we still see today."

It has long been suggested that other great Bronze Age civilisations also declined at a similar time, with a global-scale climate event being seen as the cause. While it is possible that these local-scale processes were linked, the real archaeological interest lies in understanding the impact of these larger-scale events on different environments and different populations.

"Considering the vast area of the Indus Civilisation with its variable weather systems," explained Singh, "it is essential that we obtain more climate data from areas close to the two great cities at Mohenjodaro and Harappa and also from the Indian Punjab."

"Inevitably, the weakening monsoon must have had some impact on the population," added Petrie. "We now have people looking at the detailed archaeological record and the seed grains that people were using. We're trying to work out whether the grains were grown under extreme conditions of water stress and whether they were adjusting the combinations of crops they were growing for different weather systems. We are really trying to understand details of how people led their lives. This includes looking at whether the types of pottery that they used and other aspects of their material culture were distinctive to specific regions or were more similar across larger areas. This gives us insight into the types of interactive networks that the population was involved in, and whether those changed."

Petrie believes that archaeologists are in a unique position to investigate how past societies responded to environmental and climatic change: "How did these populations cope with less water? Were their existing ways of life resilient? Were they forced to adapt to survive and, if so, what did they do?

"By investigating responses to environmental pressures and threats," he added, "we can hopefully learn from the past to engage with the public, and the relevant governmental and administrative bodies, to be more proactive in issues such as the management and administration of water supply, the balance of urban and rural development, and the importance of preserving cultural heritage in the future."

Left to right

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GETTING THE TRUE MEASURE OF PREGNANCY

“Our primary aim is to generate clinically useful screening tests that allow us to focus medical care on women who are truly high risk for complications”

One in 200 babies dies before birth in the UK. A study aimed at determining how to reduce the risk of a pregnancy coming to a devastating end is now producing its first results.

“I’ve spoken to many bereaved parents and the loss of a baby has a profound and life-long impact,” said Gordon Smith, Professor of Obstetrics and Gynaecology. “There’s a whole life to be gained if you identify a baby who will die in the womb at 40 weeks of pregnancy, and this huge gain can be achieved relatively easily by early delivery of the baby at 38 or 39 weeks.”

Smith leads the Pregnancy Outcome Prediction (POP) study, which aims to determine both the risk women face of losing their baby during their first pregnancy and how this can be reduced.

Although some women are identified as high risk for pregnancy complications from their family or medical history – and might be offered ultrasound, biochemical screening and genetic analysis, as well as an early delivery if their baby should show signs of difficulty – most stillbirths occur in women with no known risk factors.

For these low-risk women, the current provision of antenatal care – established in 1929 – still relies on the use of a tape measure.

“We estimate that over half of the 4,000 stillbirths a year in the UK are the result of placental dysfunction, which is frequently associated with impaired growth of the fetus. Apart from urine and blood pressure monitoring for pre-eclampsia – one of the conditions that can cause stillbirth – the standard means of identifying a baby that’s small for gestational age in low-risk women is measuring the mother’s ‘bump’ with a tape measure,” Smith explained.

Globally, every year 2.6 million babies are stillborn and 3.2 million live-born children die in the first month of life.

"Growth-restricted and premature children can also suffer difficulties at delivery, childhood diseases, and educational, social and health problems in later life. The emotional cost to families, coupled with the associated healthcare and social costs, means that research into the prevention of these conditions is more crucial than ever."

Smith's approach in the Department of Obstetrics and Gynaecology, funded by the National Institute for Health Research (NIHR), was to monitor more than 4,500 women during their first pregnancy at several stages until the end of pregnancy. As well as regular ultrasound scans and blood sampling, maternal and paternal DNA samples were taken and, at the time of delivery, samples of placenta, fetal membranes and umbilical cord were collected, together with details of the delivery and baby.

Completed a few months ago, the study has been a massive undertaking, but one that Smith says has laid the basis for years of in-depth analysis: "With this core resource of data and biological samples we can now ask whether there are novel biomarkers to identify women at high risk of developing pre-eclampsia – something that would be especially useful in low – and middle-income countries where scanning may not be available. We can also ask questions such as is inflammation of the placenta more common in complicated pregnancies and can this be detected by measuring circulating markers?"

One of the first questions the team asked was how effective routine ultrasound scans are as a screening test for babies who are small for gestational age; such babies are thought to account for about 30–40% of stillbirths.

"Although previously published research had shown no beneficial effect of routine screening for identifying small babies in the third trimester of pregnancy," said Smith, "it was unclear whether this was because ultrasound performed poorly as a screening test, or whether the associated interventions were ineffective." Smith and colleagues have now clearly shown that routinely scanning women during pregnancy increases the detection of the smallest babies from 32% to 77%.

"The problem with previous studies is that they were designed without any information on how well scanning performed as a screening test. We now know that ultrasound actually performs very well compared with screening tests used in other areas of medicine. We are now focusing on how to differentiate between healthy small babies and those who are small due to a pathological process. When we can achieve this, we will be able to identify the babies most likely to benefit from intervention."

"Practice only changes when guidelines change, and guidelines only change when the evidence to support change is strong," said Smith. "When we have refined our screening test, a next step may be large-scale trials of screening. The interventions will include more-intensive monitoring and earlier delivery."

The situation with stillbirth has parallels with sudden infant death syndrome (Sids), explained Smith: "In the 1980s, 1 in 500 babies died of Sids. But when research showed that sleeping on the front was a risk factor for the baby, this was followed by a public health campaign that reduced Sids by 80–90%. Although the strategy to reduce stillbirth is unlikely to be as simple, one area that we can look at is whether we can generate biomarkers for the antecedents of stillbirth, and use these for population-based screening."

Smith believes that placental dysfunction might result in 'a signature' of biomarkers that can be used to identify a problem with the placenta even in a mother showing no symptoms, and he and others have identified several potential candidates.

Many of these studies address identifying a failing placenta. However, what remains uncertain is why the placenta is dysfunctional in the first place. "One possible initiating factor is infection. Consistent with this, some studies have reported high rates of placental inflammation in pregnancies with adverse outcomes, but the evidence so far is poor."

The search for an infectious agent, possibly even a currently unrecognised bacterium or virus, has now begun, thanks to a new four-year £1.6 million project funded by the Medical Research Council using the data and biological samples gathered by the POP study. Smith and colleagues will be working with Professor Sharon Peacock from the Department of Medicine and Dr Julian Parkhill and Professor Paul Kellam from the Wellcome Trust Sanger Institute, as well as industrial partners.

It's an intriguing possibility that some hitherto unrecognised infectious agent might lead to a significant proportion of pregnancy complications. If so, there would be the possibility of treatment or vaccination to prevent complications, in the same way that women are now vaccinated against human papilloma virus to prevent cervical cancer.

"That said, the idea that we could come up with one magic solution for pre-eclampsia or stillbirth is beyond everyone's expectations at the moment. More realistically, it would seem plausible that diverse infectious agents could impair the function of the placenta, perhaps by activating some common pathway," he explained.

The overarching goal of the Department's research is to apply state-of-the-art approaches in clinical study design, biostatistics, molecular biology and sequencing to develop novel tools that will help differentiate between a healthy and an unhealthy pregnancy. "Our primary aim is to generate clinically useful screening tests that allow us to focus medical care on women who are truly high risk for complications, and to avoid 'medicalising' the experience of pregnancy and birth for the women who are at low risk."

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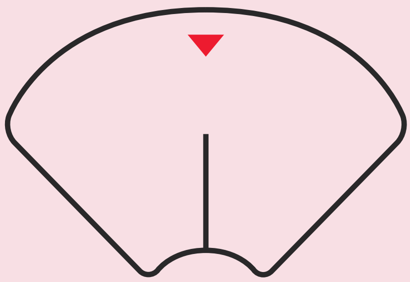

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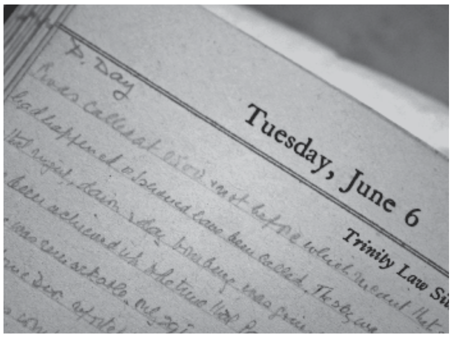


Things

D-Day's forgotten commander

Images
Photos and Ramsay's diary

Film available online

"Our task in conjunction with the Merchant Navies of the United Nations, and supported by the Allied Air Forces, is to carry the Allied Expeditionary Force to the Continent… Let no one underestimate the magnitude of this task."

The message above was delivered by Admiral Sir Bertram Ramsay on 31 May, 1944. The 'task' was launching perhaps the biggest amphibious invasion in the history of warfare, the success or failure of which would likely decide the outcome of the Second World War. Six days later, on D-Day, after years of top-secret planning, Ramsay was in overall command of Operation Neptune as more than 4,000 ships and landing craft, nearly 200,000 men and thousands of aircraft took part in the first wave of Normandy landings.

Seventy years on, Admiral Ramsay has become D-Day's forgotten commander; his pivotal role in organising what one historian described as a "never surpassed masterpiece of planning" is largely overlooked. However, naval historian and biographer Andrew Gordon, with the help of the Churchill Archives Centre, in Churchill College, Cambridge, aims to bring Ramsay's war-winning role back into the limelight.

Ramsay's personal archive, held alongside the papers of Winston Churchill, Margaret Thatcher and others at the Archives Centre, has been an invaluable resource for Gordon during his research for the upcoming biography on Ramsay.

The Ramsay Archive includes his D-Day diary, invasion maps, photographs and correspondence – as well as eyewitness accounts from the Dunkirk evacuation, another momentous occasion in British naval history overseen by Ramsay.

The collection spans his career from life as a midshipman to D-Day and beyond, until Ramsay's untimely death in a plane crash in 1945, when his aircraft crashed in France, en route to meet Field Marshal Montgomery in Brussels.

The Churchill Archives Centre is home to the papers of almost 600 important political, military and scientific figures in 20th-century British history.

www.chu.cam.ac.uk/archives

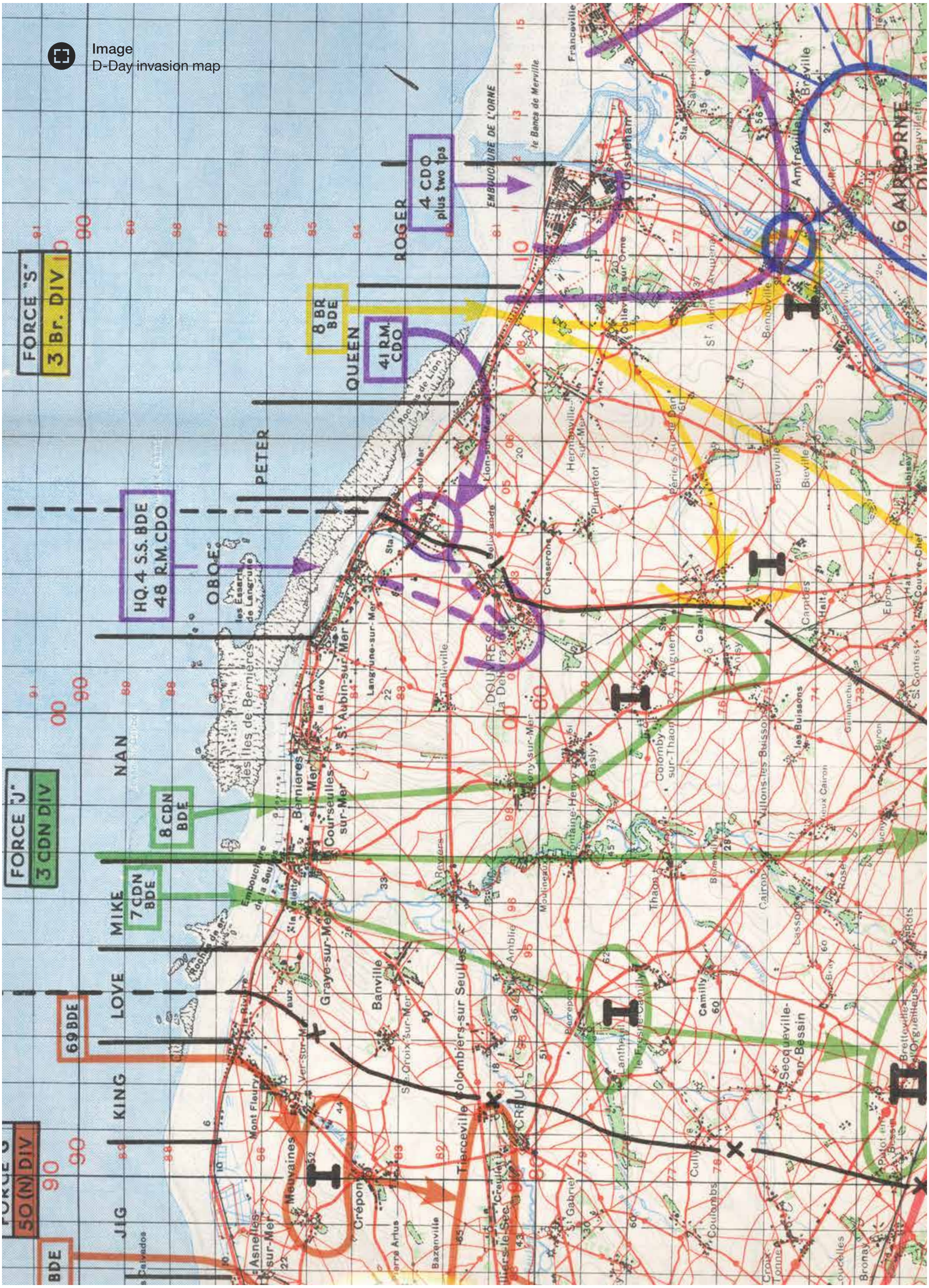
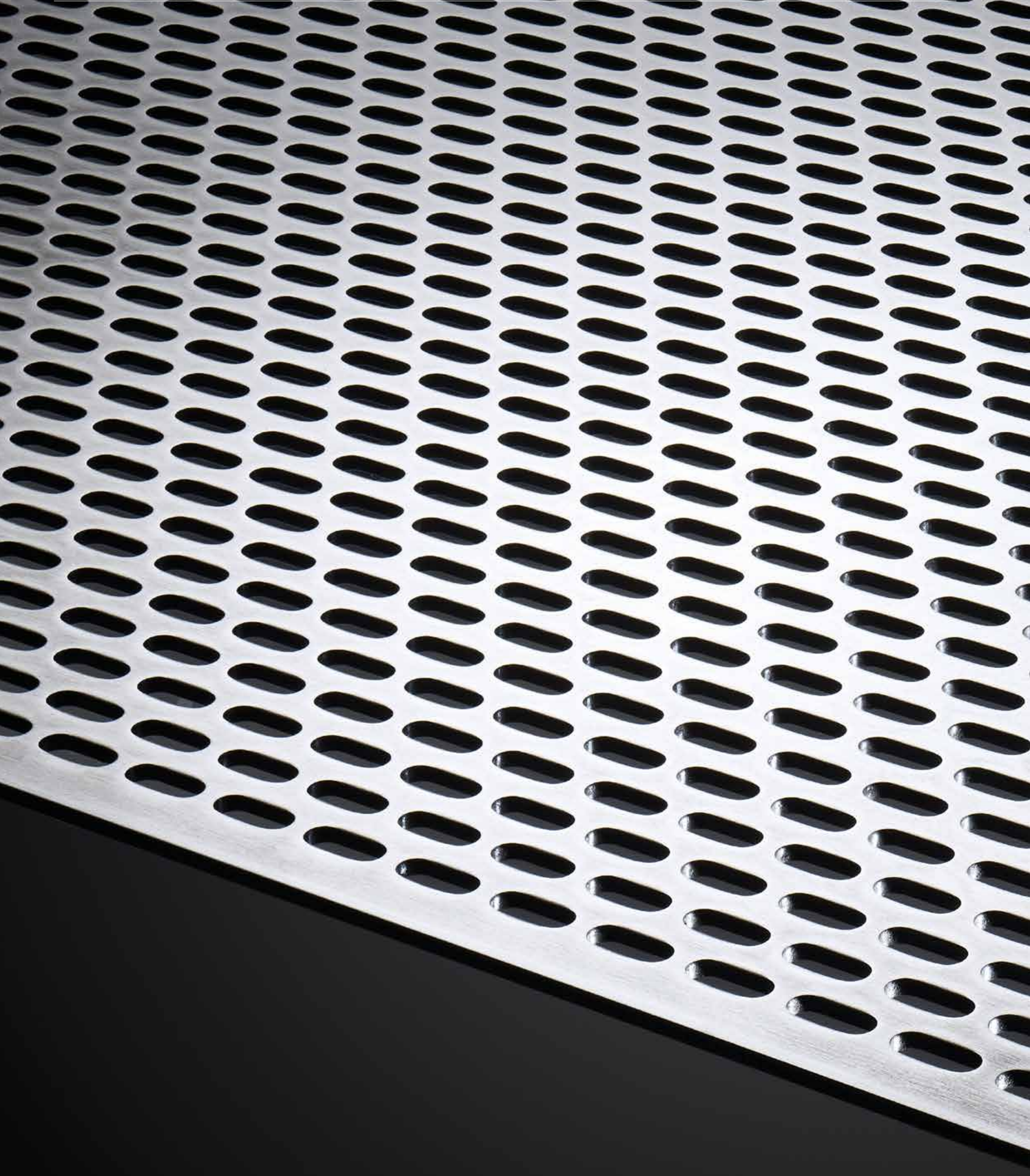


Image
D-Day invasion map



Steel’s inner strength

Image
Perforations in super bainite make the material even better at protecting armoured vehicles from projectiles

By heat-treating steel at temperatures closer to those that are normally used for baking cakes, for 10 or more days, a new form results...

A long-term collaboration between the University and industry has resulted in a super-strong form of steel, which is now being manufactured in the UK for use as stronger and cheaper armour for front-line military vehicles.

For thousands of years, steel has been used to make or do just about whatever we ask of it, from ancient suits of armour to modern skyscrapers. It has been mass produced since the mid-19th century, and global production of this most ubiquitous of materials currently stands at more than 1.4 billion metric tonnes per year.

Although all steel consists primarily of iron and carbon, it has an almost infinite variety of properties, depending on the type or amount of other elements added to the mix, or the temperature at which the steel is produced. This complexity makes steel extremely versatile, but also very difficult to understand and to design from the atomic level.

Professor Harry Bhadeshia of the Department of Materials Science and Metallurgy has spent the past three decades researching the nature of steel to develop new alloys for a range of applications. One of these alloys, super bainite, has been licensed to Tata Steel and is currently being manufactured in the UK by the company for use as super-strong armour for military vehicles, as well as for other applications.

Bainite is a microstructure that forms when austenite, a high-temperature phase of steel, is cooled to temperatures between 250 and 500°C. The structure of austenite transforms as it cools, when slender crystals of iron incorporate themselves into the structure, and carbon compounds known as carbides form. The resulting bainite structure is very hard, but the carbides make it brittle and prone to cracking.

Working in collaboration with Professor Peter Brown of the Ministry of Defence (MoD), Bhadeshia and Dr Francisca Caballero in the Department of Materials Science and Metallurgy set out to refine and enhance the properties of bainite, originally for use in gun barrels.

Using precise modelling, they determined that there is no lower limit to the temperature at which bainite can be produced. By heat-treating it at temperatures around 200°C – closer to those that are normally used for baking cakes rather than for manufacturing steel – for 10 or more days, a new form results: super bainite. In addition, by adding elements such as silicon and molybdenum, carbides and harmful impurity phases are prevented from forming in the steel, reducing the likelihood of cracks.

Super bainite is strong – very strong. With a tensile strength of some 2.5 gigapascals, just one square metre can support a weight equivalent to the weight of 2.5 billion apples. It has a higher density of interfaces than any other type of metal, and is the world's first bulk nanostructured metal.

The strength of super bainite derives not only from the lack of carbides, but also from the tiny size of the iron crystals within its structure. Most types of steel are made up of very fine crystals: the smaller and finer the crystals, the stronger the resulting steel will be. The crystals in super bainite are between 20 and 40 nanometres thick, comparable to the width of carbon nanotubes. In comparison, the crystals in conventional bainite are between 200 and 500 nanometres thick.

"The size of these crystals means that the steel is very difficult to deform, resulting in a more perfect structure," said Bhadeshia. "And because of the very slow cooking process, which is actually quite simple, we can make the steel in very large quantities at low cost."

The cooking time resulted in a product with highly desirable characteristics, but the long wait meant that super bainite was only suitable for certain commercial applications. Supported by funding from the Engineering and Physical Sciences Research Council and the MoD, Dr Carlos Mateo (also from Cambridge), Brown and Bhadeshia set out to accelerate the process. Through the use of kinetic and thermodynamic modelling, they found that by tailoring the composition of super bainite and heat-treating it at slightly higher temperatures, up to 250°C, it could be manufactured in a matter of hours rather than days, without any significant loss in performance.

In 2011, super bainite was licensed to Tata Steel, one of the world's largest steel producers. Tata is now manufacturing the material at its facility at Port Talbot in South Wales, which is the first time that high-carbon steel has been manufactured on a large scale in the UK for 20 years. It is currently available commercially for civil applications such as automated teller machines for dispensing money, and as super-strong armour for use on military vehicles, under the name Pavise™.

Brown and his colleagues at the MoD's Defence Science and Technology Laboratory at Porton Down determined that, counter-intuitively, perforations bored into super bainite made it even more capable of protecting vehicles from projectiles.

"The ability of perforated super bainite steel to resist projectiles is at least twice that of conventional monolithic rolled homogeneous armour," said Brown. "By introducing perforations into the steel, we create a large number of edges, which interrupt the path of incoming projectiles."

Super bainite's enormous strength makes it ideal for these types of applications, where strength and toughness are paramount. In addition to defence applications, there are spin-off high-carbon alloys for which the demand in Europe is up to 400,000 tonnes each year, for items such as springs, bearing cages and hand tools, where hard and thin sheets of steel are required. About 80% of these high-carbon steels that are being manufactured in Wales are now exported to markets worldwide.

"In addition to its superior ballistic properties, Pavise™ is manufactured in a far simpler way than other commercially available ballistic armour, and its performance comes from its unique properties," said Kevin Edgar, Head of Marketing, Engineering Sectors at Tata Steel. "Other armours have long lead times owing to complex production routes, whereas we can produce this product alongside regular production runs, which means we can react more quickly to what the end users require and work with them – this flexibility gives us a real advantage."

The researchers in Bhadeshia's group are now working with their partners in industry to address super bainite's main weakness which, ironically, is its strength. "As it is so strong, super bainite cannot be welded, so it cannot be made into very large structures where pieces need to be joined together," he said. "We are again working with MoD to further refine the structure so that it can be welded, without losing the characteristics that make it such a unique and high-performing material."

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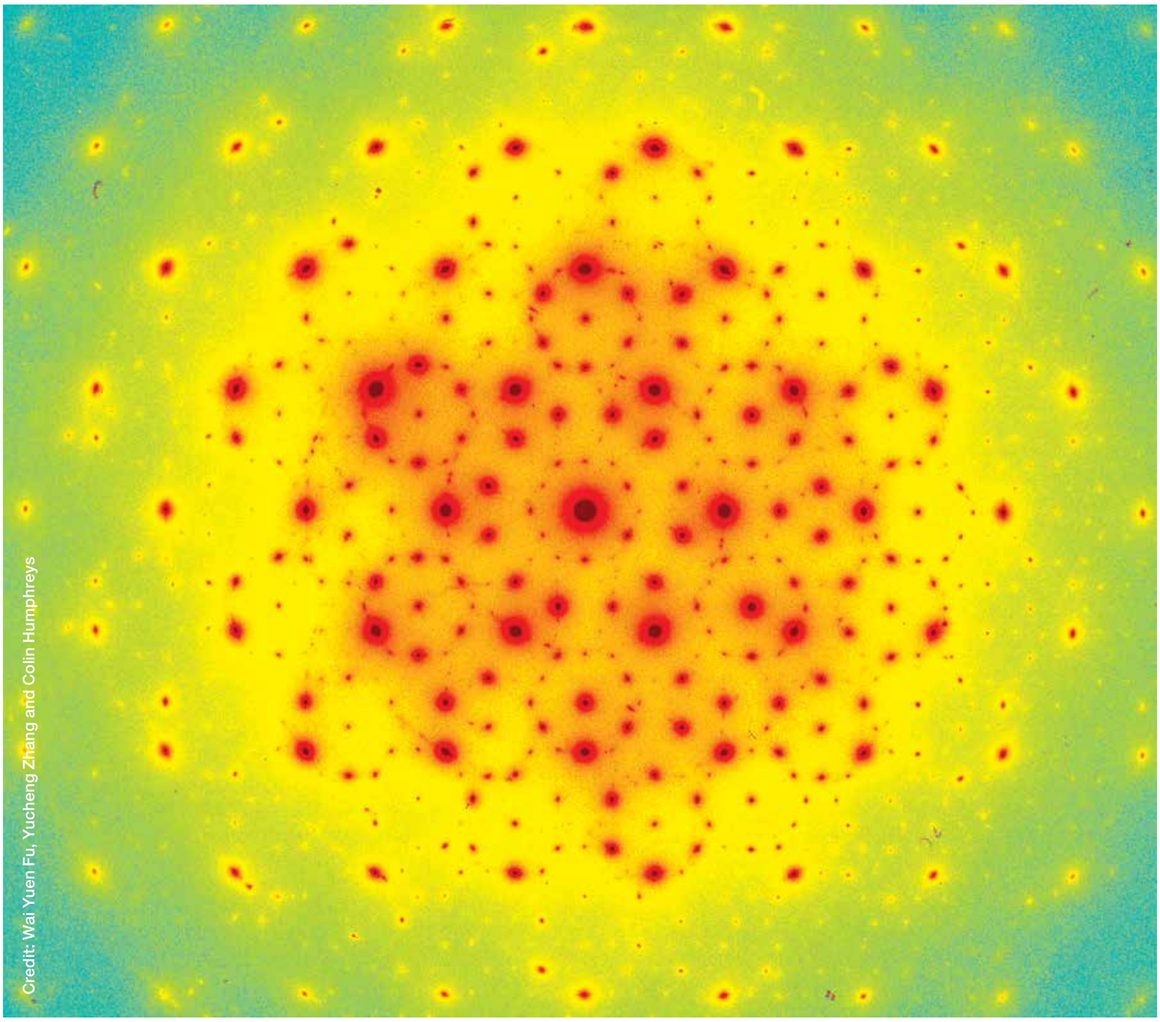
Image
Electron diffraction pattern of a thin film made of gallium nitride



Out of the red and into the blue: making the LED revolution cost-effective

British manufacturer Plessey Semiconductors is racing to be the first company to make energy-efficient LEDs for home lighting at a price that consumers will pay, and they're using a technology developed by Cambridge researchers.

In 2012, Plessey acquired technology to grow a remarkable man-made material that can emit light in every part of the colour spectrum when electricity passes through it. They recommissioned a mothballed processing plant, created new jobs and hired three researchers from the University of Cambridge. Their aim: to put energy-efficient lighting within financial reach of the consumer.

Prototypes of their light-emitting diodes (LEDs) rolled off the production line later that year, and by April 2013 the company was gearing up to fulfil its first commercial orders. In just 15 months, Plymouth-based Plessey had gone from never having made an LED to being the world's first manufacturer of commercially available LEDs made on large-diameter silicon substrates.

LEDs can last for 100,000 hours compared with 10,000 hours for fluorescent tubes and 1,000 hours for tungsten filament light bulbs

Today, the company is addressing a global market that, according to a report released in 2013 by WinterGreen Research, could be worth up to $42 billion by 2019. What gives Plessey an edge over its competitors is its ability to manufacture LEDs at a fraction of their costs, thanks to a unique process developed by Professor Sir Colin Humphreys in the Cambridge Centre for Gallium Nitride.

Blue and white gallium nitride (GaN) LEDs have been commercialised around the world since Shuji Nakamura in Japan developed a method of growing thin GaN layers on sapphire in the early 1990s. Although GaN LEDs are now expected to dominate the world market for lighting, their performance and cost both need to be improved.

Humphreys' team has developed a way of growing GaN on the vastly cheaper substrate silicon and, crucially, a means of scaling this up for commercial purposes. "We've got lower costs for growing GaN LEDs on silicon than anyone else we know," explained Humphreys. "Potentially, this is an advantage that puts Britain right at the forefront of LED research."

Competition between manufacturers (including Toshiba and Samsung) to lead the market in competitively priced LEDs has been intense, driven by the increasing demand for energy-efficient lights.

LED bulbs have much longer working lives than any other forms of artificial lighting: LEDs can last for 100,000 hours compared with 10,000 hours for fluorescent tubes and 1,000 hours for tungsten filament light bulbs. LEDs in dashboards frequently outlive the life of the car; LED light bulbs in the home would probably have to be changed only once in a person's lifetime.

LEDs also use less energy than other forms of lighting. UK homes use 20% of their energy on lighting and, because LEDs use 90% less energy than incandescent bulbs, Humphreys estimates that the superior energy efficiency of LEDs could save the UK £2 billion per year in energy, and reduce CO_2 emissions. It's little wonder that LEDs have been hailed as a lighting revolution.

Yet, few homeowners have invested in LEDs for home lighting. "A 48-watt equivalent LED bulb costs around £15. Although it will save people money over its lifetime, very few people will pay this. We think we can reduce the cost to £3," said Humphreys.

Humphreys' team has pioneered a technique for depositing successive layers of GaN and indium GaN, each only 5–10 atoms thick and growing at the speed of grass, on a six-inch silicon wafer. The wafer is then cut into up to 150,000 pieces, each of which forms the heart of a small LED. Using this technology, Plessey hopes to become the commercial leader in GaN-on-silicon LEDs, producing billions per year.

"Growing GaN on silicon is quite a complex process," said Humphreys. A particular problem is the appearance of cracks on cooling from the growth conditions of 1,000°C. This has now been solved by the researchers through careful balancing of the tension in the material as it cools down.

Plessey acquired the technique when it bought the spin-out company CamGaN, set up by Humphreys and colleagues to commercialise the technology. The size of the silicon wafers is greater than the conventional two-inch sapphire wafers, meaning a greater number of LEDs can be made. Fortuitously, Plessey had a six-inch processing line that had been mothballed.

"When we launched CamGaN, we were contacted by companies all over the world wanting to utilise the technology," said Humphreys. "The research has been funded by government money through the Engineering and Physical Sciences Research Council (EPSRC) and it was important to us that this research be exploited here in the UK."

Meanwhile, the researchers are continuing their work with what Humphreys describes as a "truly remarkable" material. A new £1 million growth facility funded by the EPSRC and made by AIXTRON Ltd, a long-term collaborator of Humphreys' research group, has been installed in Cambridge, where the researchers are adjusting minute aspects of the growth process to improve the efficiency of light emission.

The benefits of increased efficiency could go far beyond home lighting, and the researchers are now looking at applications that extend from biomedicine to power electronics.

In collaboration with the University of Manchester, they plan to build tiny LED devices that can be implanted by keyhole surgery in cancer patients being treated with radiotherapy. "If a patient moves while an X-ray or proton beam is directed at their tumour, then they risk healthy tissue being damaged," explained Humphreys. "An LED attached to a sensor would detect movement at the site of the tumour in order to redirect the beam."

Even tinier devices are being investigated as a means of firing single neurons in the brain. Working with US researchers involved in the Brain Activity Map Project – a flagship initiative of the Obama administration – the researchers will supply LEDs that can be implanted in the brain with the goal of mapping the activity of every neuron, to understand how the brain works both in health and disease.

Water purification is another area where LEDs could benefit the health of millions. "Life on earth has developed in the absence of deep UV and so we can kill bacteria and viruses by damaging their DNA with deep UV light," he said. The idea is to have a ring of LEDs powered by solar cells on the inside of water pipes. "We now have LEDs with the right energy level to do this, we just need to increase the intensity."

Collaborative projects with the Universities of Glasgow and Strathclyde are also investigating GaN transistors as power electronics in devices that manage electrical energy and LEDs as light-based Wifi (so-called Li-Fi). Humphreys believes that the day will arrive when GaN devices will light our homes, power our mobile phones, laptops, cars and aircraft engines, and connect us wirelessly to information transmitted from traffic lights and street lights.

"In addition to the £2 billion per year in electricity savings from GaN LEDs, GaN transistors could help the UK save £1 billion from power electronics and 15–20% in carbon emissions, and GaN UV LEDs could save millions of lives," said Humphreys. "It's the ultimate shopping list."

Plessey, in the meantime, is focusing on product improvement and reduction in cost. "There are huge players in the market but we were first to market with GaN-on-silicon LEDs," said Dr Keith Strickland Chief Technology Officer of Plessey. "Our continuing relationship with the Cambridge research group will help us push this technology to its highest potential."

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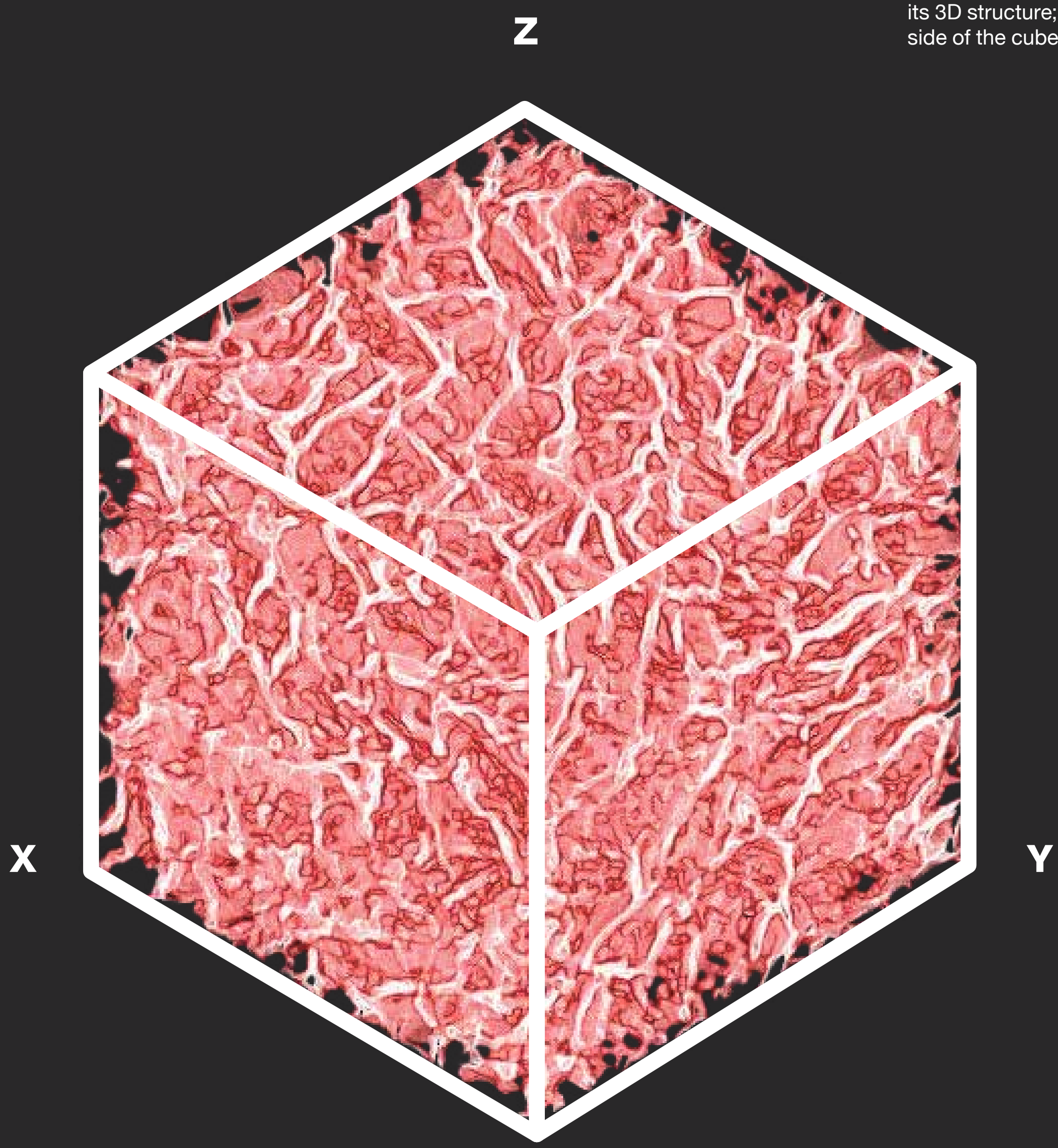
Department of Materials Science and Metallurgy

Image
Collagen scaffold imaged using X-ray microtomography to reveal its 3D structure; the length of the side of the cube is 1 mm



BODY BUILDERS

Credit: Jennifer Ashworth

Miniature scaffolds made from collagen – the 'glue' that holds our bodies together – are being used to heal damaged joints, and could be used to develop new cancer therapies or help repair the heart after a heart attack.

It may not look like much to the naked eye, but collagen is remarkably strong. The most abundant protein in the animal kingdom, it gives strength and structure to skin, tendons, ligaments, smooth muscle tissue and many other parts of the body.

Through precise manipulation at a structural level, collagen can also be used as a construction material in the laboratory or clinic to help regenerate new tissue, repair damaged cartilage and bone, or aid in the development of new therapies for cardiac disease, blood disorders and cancer.

To understand these conditions better and develop new treatments, or regenerate new tissue, researchers require models that very closely mimic the complex, three-dimensional environments found in human tissue.

As a natural material, collagen is ideal for these biomimetic applications. By shaping it into porous structures, collagen acts as a 'scaffold' on which cells and tissue can grow in three dimensions in predetermined forms, mimicking those found in the body.

The idea of using collagen as a scaffold is not new, but the very high level of control that Cambridge researchers are able to achieve over its properties has made a huge range of clinical applications possible, including the repair of damaged joints or tissue, or accelerating the development of new therapies for cancer.

"There is an increasing need for improved materials that work with the systems in the body to regenerate healthy tissue, rather than just replacing what's there with something synthetic," said Professor Ruth Cameron of the Department of Materials Science and Metallurgy, who, along with Professor Serena Best, is working with researchers from across the University to develop the scaffolds for a range of clinical applications. "You're trying to help the body to heal itself and produce what it needs in order to do that."

To build the scaffolds, the researchers begin with a solution of collagen and water and freeze it, creating ice crystals. As the collagen cannot incorporate into ice, it gathers around the edges of the crystals. When the pressure around the ice is dropped to very low levels, it converts directly from a solid to vapour, leaving the collagen structure behind. By precisely controlling how the ice crystals grow as the water freezes, the researchers are able to control the shape and properties of the resulting collagen scaffold.

By adding small groups of amino acids known as peptide sequences to the surface of the scaffold at different points, the way in which the collagen interacts with the growing cells changes, altering the potential uses for the scaffold. The peptide sequences signal certain cells to bind to the scaffold or to each other, while signalling other cells to migrate. Collectively, these signals direct the scaffold to form a certain type of tissue or have a certain type of biological response.

"The scaffolds are a three-dimensional blank canvas – they can then be used in any number of different ways," said Cameron, who is funded by the European Research Council. "They can be used to mimic the way in which natural tissue behaves, or they can be directed to form different sized or sequenced structures."

The technology has already gone from the laboratory all the way to patients, first as Chondromimetic, a product for the repair of damaged knee joints and bone defects associated with conditions such as osteoarthritis, trauma or surgery. By adding calcium and phosphate to the scaffold to mimic the structure of bone, it helps regenerate bone and cartilage. Chondromimetic has been through clinical trials and has received its CE mark, enabling its sale in Europe.

> **"It could be used in almost any situation where you're trying to regenerate tissue"**

In future, the scaffolds could also see use as a treatment for cardiac disease. Working with Professor Richard Farndale from the Department of Biochemistry and Dr Sanjay Sinha from the Department of Medicine, and supported by funding from the British Heart Foundation, Best and Cameron are developing the scaffolds for use as patches to repair the heart after a heart attack.

Heart attacks occur when there is an interruption of blood to the heart, killing heart muscle. The remaining heart muscle then has to work harder to pump blood around the body, which can lead to a thickening of the heart wall and potential future heart failure.

By modifying the collagen scaffolds with the addition of peptide sequences, they could be used to grow new heart cells to 'patch' over areas of dead muscle, regenerating the heart and helping it function normally. Cells could be taken directly from the patient and reprogrammed to form heart cells through stem cell techniques.

While the work is still in its early stages, the scaffolds could one day be an important tool in treating coronary heart disease, which is the UK's biggest killer. "These scaffolds give cells a foothold," said Farndale, who is working with Sinha to characterise the scaffolds so that they encourage heart cells to grow. "Eventually, we hope to be able to use them, along with cells we've taken directly from the patient, to enable the heart to heal itself following cardiac failure."

Another potentially important application for the scaffolds is in breast cancer research. By using them to grow mimics of breast tissue, the scaffolds could help accelerate the development of new therapies. Working with Professor Christine Watson in the Department of Pathology, Best and Cameron are fine-tuning the scaffolds so that they can be used to create three-dimensional models of breast tissue. If successful, this artificial breast tissue could assist with the screening of new drugs for breast cancer, reduce the number of animals used in cancer research and ultimately lead to personalised therapies.

"This is a unique culture system," said Watson. "We are able to add different types of cells to the scaffold at different times, which no-one else can do. Better models will make our work as cancer researchers much easier, which will ultimately benefit patients."

Like breast tissue, blood platelets also require a very specific environment to grow. Dr Cedric Ghevaert of the Department of Haematology is working with Best and Cameron to use the scaffold technology to create a bone-like niche to grow bone marrow cells, or megakaryocytes, for the production of blood platelets from adult stem cells. In theory, this could be used to produce platelets as and when they are needed, without having to rely on blood donations.

"The technology for culturing the cells is actually quite generic, so the range of applications it could be used for in future is quite broad," said Best. "In terms of clinical applications, it could be used in almost any situation where you're trying to regenerate tissue."

"In some senses, it can be used for anything," added Cameron. "As you start to create highly organised structures made up of many different types of cells – such as the liver or pancreas – there is an ever-increasing complexity. But the potential of this technology is huge. It could make a huge difference for researchers and patients alike."

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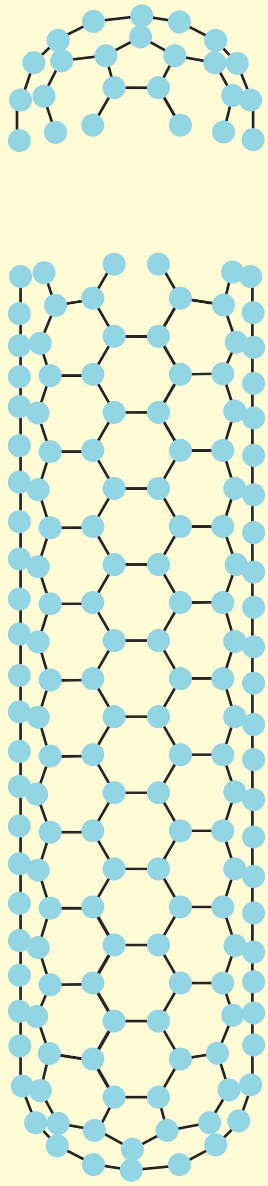

How Carbon Cousins shaped warfare and Can electrify the future

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What links legendarily sharp Damascene swords of the past with flexible electronics and high-performance electrical wiring of the future? They all owe their remarkable properties to different structural forms of carbon.

History's deadliest swords – the 'Damascene' sabres forged in the Middle East from the 13th to the 18th centuries – were so sharp they could slice through falling silk, so legend has it. Their astonishing qualities are thought to have come from a combination of specific impurities in the iron ore and how hot and how long they were fired – a process that some scientists believe may have unwittingly created carbon nanotubes (CNTs) within them.

These thin, hollow tubes are only a single carbon atom in thickness. Like their carbon cousin, graphene – in which the atoms lie flat, in a two-dimensional sheet – they are among the strongest, most lightweight and flexible materials known.

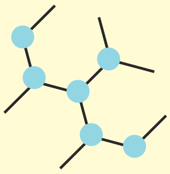
"Fast-forward centuries," said Dr Stephan Hofmann from the Department of Engineering, "and we now realise there is a whole family of these extraordinary origami forms of carbon… and how to make them." In fact, the University has over 25 years' cutting-edge experience in carbon nanotechnology, from diamond to nanotubes, and from conducting polymers to diamond-like carbon and graphene.

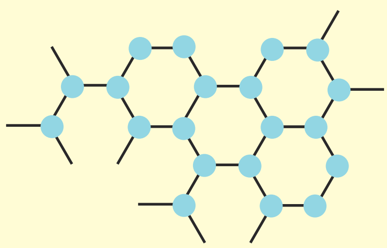
What makes carbon nanoforms such as graphene and CNTs so exciting is their electrical and thermal properties. Their potential use in applications such as lighter electrical wiring, thinner batteries, stronger building materials and flexible devices could have a transformational impact on the energy, transport and healthcare industries. As a result, investment totalling millions of pounds is now underpinning research and development in carbon-based research across the University.

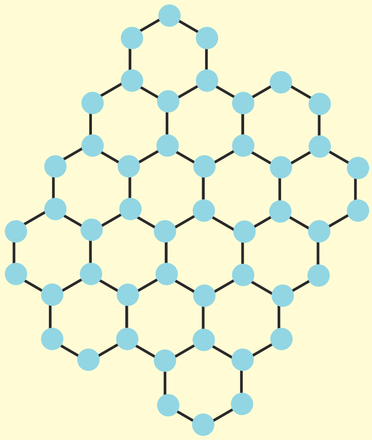
"But all of the superlatives attributed to the materials refer to an individual, atomically perfect, nanotube or graphene flake," Hofmann added. "The frequently pictured elephant supported by a graphene sheet epitomises the often non-realistic expectations. The challenge remains to achieve high quality on a large scale and at low cost, and to interface and integrate the materials in devices."

These are the types of challenges that researchers in the Departments of Engineering, Materials Science and Metallurgy, Physics and Chemistry, and the Cambridge Graphene Centre have been working towards overcoming.

Professor Alan Windle from the Department of Materials Science and







“The field is at a very exciting stage… we are beginning to understand what governs their growth and how they behave in industrially relevant environments”

Metallurgy, for instance, has been using a chemical vapour deposition process to ‘spin’ very strong and tough fibres made entirely of CNTs. The nanotubes form smoke in the reactor but, because they are entangled and elastic, fibres can be wound continuously out of the reactor like nano candy floss. The yarn-like texture of the fibres gives them extraordinary toughness and resistance to cutting, making them promising alternatives to carbon fibres or high-performance polymer fibres like Kevlar, as well as for building tailored fibre-reinforced polymers used in aerospace and sports applications.

It is on the electrical front that they meet their greatest challenge, as Windle explained: “The process of manufacture is being scaled up through a Cambridge spin-out, Q-Flo; however, electrical conductivity is the next grand challenge for CNT fibres in the laboratory. To understand and develop the fibre as a replacement for copper conductors will be world-changing, with huge benefits.”

In 2013, Windle’s colleague Dr Krzysztof Koziol succeeded in making electric wiring made entirely from CNT fibres and developing an alloy that can solder carbon wires to metal, making it possible to incorporate CNT wires into conventional circuits. The team now makes wires ranging from a few micrometres to a few millimetres in diameter at a rate of up to 20 metres per minute – no small feat when you consider each CNT is ten thousand times narrower than a human hair.

With funding from the Royal Society and the European Research Council (ERC), the research is aimed at using CNTs to replace copper and aluminium in domestic electrical wiring, overhead power transmission lines and aircraft. CNTs carry more current, lose less energy in heat and do not require mineral extraction from the earth.

Moreover, they can be made from greenhouse gases; Koziol’s team is working with spin-out company FGV Cambridge Nanosystems to become the world’s first company to produce high-grade CNTs and graphene directly from natural gas or contaminated biogas. The company is already operating at an industrial scale, with high-purity graphene being produced at 1 kg per hour. “The aim is to produce high-quality materials that can be directly implemented into new devices, or used to improve other materials, like glass, metal or polymers,” said Koziol.

Working directly with industry will be key to speeding up the transition from lab to factory for new materials. Hofmann is leading a large effort to develop the manufacturing and integrated processing technology for CNTs, graphene and related nanomaterials, with funding from the ERC and Engineering and Physical Sciences Research Council (EPSRC), and in collaboration with a network of industrial partners.

“The field is at a very exciting stage,” he said, “now, not only can we ‘see’ and resolve their intricate structures, but new characterisation techniques allow us to take real-time videos of how they assemble, atom by atom. We are beginning to understand what governs their growth and how they behave in industrially relevant environments. This allows us to better control their properties, alignment, location and interfaces with other materials, which is key to unlocking their commercial potential.”

For high-end applications in the electronics and photonics industry, achieving this level of control is not just desirable but a necessity. The ability to produce carbon controllably in its many structural forms widens the ‘materials portfolio’ that a modern engineer has at their disposal. With carbon films or structures already found in products such as hard drives, razor blades and lithium ion batteries, the industrial use of CNTs is becoming increasingly widespread, driven, for instance, by the demand for new technologies such as flexible devices and our need to harvest, convert and store energy more efficiently.

Professor Andrea Ferrari, Director of the Cambridge Graphene Centre and doctoral training programme, which has been funded through a £17 million grant from the EPSRC, explained: “People can now make graphene by the tonne – it’s not an issue. The challenge is to match the properties of the graphene you produce with the final application. Our facilities and equipment have been selected to promote alignment with industry; we have collaborations with over 20 companies who share our agenda of advancing real-life applications, and many more are discussing their involvement with our activities.”

Cambridge has pioneered graphene engineering and technology from the very start and, with multiple spin-offs, has become a hub for graphene manufacturing and innovation. The Cambridge Graphene Centre aims to improve manufacturing techniques for graphene and related materials, as well as explore applications in the areas of energy storage and harvesting devices, high-frequency electronics, photonics, flexible and wearable electronics, and composites. Graphene is also the focus of large-scale European funding – the Graphene Flagship, a pan-European 10-year, €1 billion science and technology programme was launched in 2013. Ferrari was one of the key investigators who prepared the proposal, has led the development of the science and technology roadmap for the project, and now chairs the Flagship’s Executive Board.

Now, building work has begun on a £12.9 million bespoke facility that will host the Cambridge Graphene Centre, with additional spaces for large-area electronics. The facility is due to open in late spring 2015.

“We recognise that there is still much to be done before the early promise becomes reality, but there are major opportunities now,” said Ferrari. “We are at the beginning of a journey. We do not know the final outcome, but the potential of graphene and related materials is such that it makes perfect sense to put a large effort into this early on.”

I

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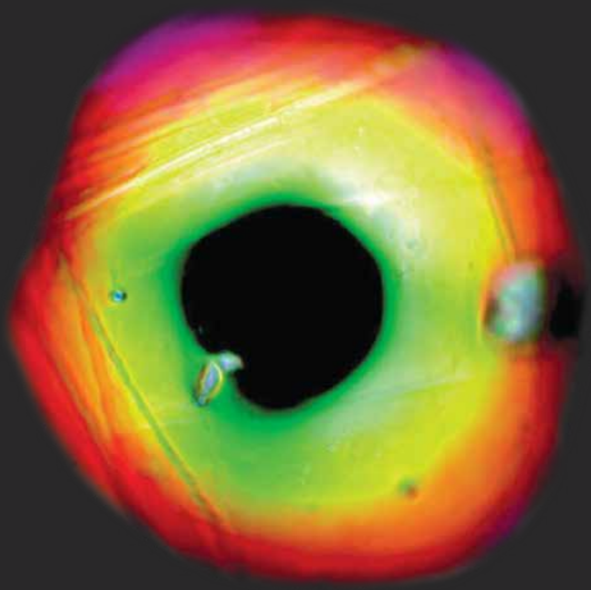
Trapping the light fantastic

Image
Light can be manipulated at the nanoscale, as in this elastic material which has been folded like nano-origami



The development of a 'nanobarrel' that traps and concentrates light onto single molecules could be used as a low-cost and reliable diagnostic test.

Jeremy Baumberg and his 30-strong team of researchers are master manipulators of light. They are specialists in nanophotonics – the control of how light interacts with tiny chunks of matter, at scales as small as a billionth of a metre. It's a field of physics that 20 years ago was unknown.

At the heart of nanophotonics is the idea that changing the structure of materials at the scale of a few atoms can be used to alter not only the way light interacts with the material, but also its functional properties.

"The goal is to design materials with really intricate architecture on a really small scale, so small it's smaller than the wavelength of light," said Baumberg, Professor of Nanophotonics in the Department of Physics. "Whether the starting material is polystyrene or gold, changing the shape of its nanostructure can give us extraordinary control over how light energy is absorbed by the electrons locked inside. We're learning how to use this to develop new functionality."

One of their recent achievements is to develop synthetic materials that mimic some of nature's most striking colours, among them the iridescent hue of opals. Naturally occurring opals are formed over millions of years at intense temperature and pressure, and consist of perfectly ordered glass spheres that diffract light.

'Polymer opals', however, are plastic – like the polystyrene in drinking cups – and formed within a matter of minutes. With some clever chemistry, the researchers have found a way of making polysterene spheres coated in a soft chewing-gum-like outer shell.

As these polymer opals are twisted and stretched, 'metallic' blue–green colours ripple across their surface. Their flexibility and the permanence of their intense colour make them ideal materials for security cards and banknotes or to replace toxic dyes in the textile industry.

"The crucial thing is that by assembling things in the right way you get the function you want," said Baumberg, who developed the polymer opals with collaborators in Germany (at the DKI, now the Fraunhofer Institute for Structural Durability and System Reliability). "If the spheres are random, the material looks white or colourless, but if stacked perfectly regularly you get colour. We've found that smearing the spheres against each other magically makes them fall into regular lines and, because of the chewing gum layer, when you stretch it the colour changes too.

"It's such a good example of nanotechnology – we take a transparent material, we cut it up in the right form, we stack it in the right way and we get completely new function."

Credit: Gen Kamita and Jeremy Baumberg

Although nanophotonics is a comparatively new area of materials research, Baumberg believes that within two decades we will start to see nanophotonic materials in anything from smart textiles to buildings and food colouring to solar cells.

Now, one of the team's latest discoveries looks set to open up applications in medical diagnostics.

"We're starting to learn how we can make materials that respond optically to the presence of individual molecules in biological fluids," he explained. "There's a large demand for this. GPs would like to be able to test the patient while they wait, rather than sending samples away for clinical testing. And cheap and reliable tests would benefit developing countries that lack expensive diagnostic equipment."

"Eventually... we will be able to build things with light itself"

A commonly used technique in medical diagnostics is Raman spectroscopy, which detects the presence of a molecule by its 'optical signature'. It measures how light is changed when it bounces off a molecule, which in turn depends on the bonds within the molecule. However, the machines need to be very powerful to detect what can be quite weak effects.

Baumberg has been working with Dr Oren Scherman, Director of the Melville Laboratory for Polymer Synthesis in the Department of Chemistry, on a completely new way to sense molecules they have developed using a barrel-shaped molecular container called cucurbituril (CB). Acting like a tiny test tube, CB enables single molecules to enter its barrel shape, effectively isolating them from a mixture of molecules.

In collaboration with researchers in Spain and France, and with funding from the European Union, Baumberg and Scherman have found a way to detect what's in each barrel using light, by combining the barrels with particles of gold only a few thousand atoms across.

"Shining light onto this gold–barrel mixture focuses and enhances the light waves into tiny volumes of space exactly where the molecules are located," Baumberg explained. "By looking at the colours of the scattered light, we can work out which molecules are present and what they are doing, and with very high sensitivity."

Whereas most sensing equipment requires precise conditions that can only really be achieved in the laboratory, this new technology has the potential to be a low-cost, reliable and rapid sensor for mass markets. The amount of gold required for the test is extremely small, and the gold particles self-assemble with CB at room temperature.

Now, with funding from the Engineering and Physical Sciences Research Council, and working with companies and potential end users (including the NHS), Baumberg and Scherman have begun the process of developing their 'plasmonic sensors' to test biological fluids such as urine and tears, for uses such as detecting neurotransmitters in the brain and protein incompatibilities between mother and fetus.

"At the same time, we want to understand how we can go further with the technology, from controlling chemical reactions happening inside the barrel, to making captured molecules inside 'flex' themselves, and detecting each of these modifications through colour change," added Baumberg.

"The ability to look at small numbers of molecules in a sea of others has appealed to scientists for years. Soon we will be able to do this on an unprecedented scale: watching in real time how molecules come together and undergo chemical reactions, and even how they form a bond. This has huge implications for optimising catalysis in industrially relevant processes and is therefore at the heart of almost every product in our lives."

Baumberg views nanophotonics technology as a whole new toolbox. "The excitement for me is the challenge of how difficult the task is combined with the fact that you can see that, if only you could do it, you can get things out that are incredible.

"At the moment we are capable of assembling new structures with different optical properties in a highly controlled way. Eventually, though, we will be able to build things with light itself."

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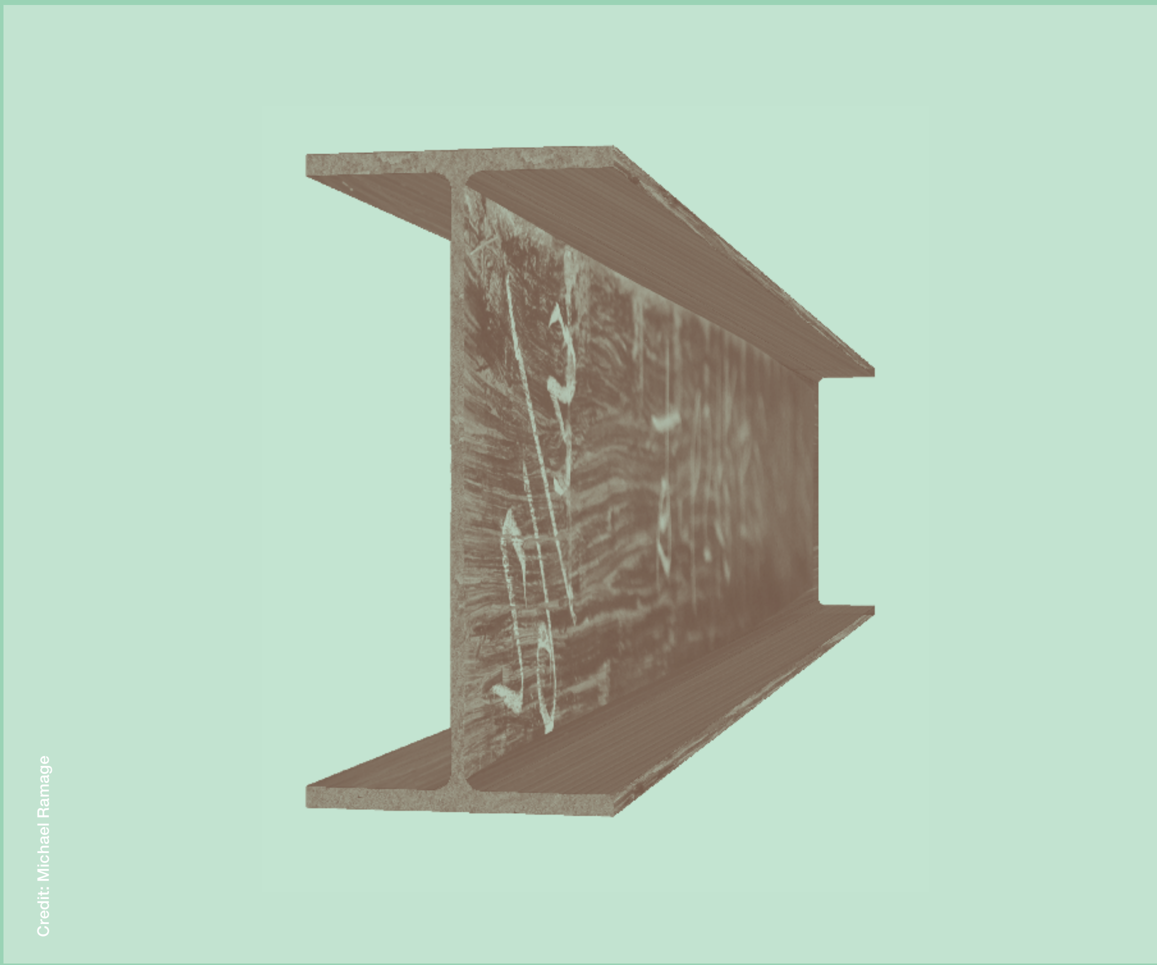

Credit: Michael Ramage

Seeds to SKYSCRAPERS

Image
Bamboo I-beam

Wood is one of the oldest building materials but its use is limited by its properties. With new funding, researchers aim to stretch these properties to an unprecedented degree, creating the means to build a skyscraper out of plants.

It's not often that research begins with designing a wooden 70-storey office building that falls over, at least on paper. But this is what a group of architectural engineers in Cambridge did to demonstrate that wood is simply not up to the task.

Today, almost all new large-scale buildings are constructed using concrete and steel. Valued for their strength, flexibility and stability, these materials are nonetheless notoriously energy-intensive, with the manufacturing of construction materials for buildings suggested to account for around 5% of total UK emissions. Indeed, CO_2 emissions embodied in how the fabric of the building is constructed can be just as significant as the operational emissions once it is occupied.

"It's doubtful that much can be done to bring down the energy used in traditional manufacturing of concrete and steel. Primary savings will come only through demand reduction, including switching to other materials," explained Michael Ramage, the architect behind the experimental wooden skyscraper. "We think there are tremendous opportunities for novel plant-based materials in construction but, as our skyscraper showed, the material itself must be redesigned.

"Forensic engineering showed that once our test building reached a certain height the wood at the bottom began to crush. We want to redesign wood from the molecular level to create some of the most advanced and sustainable construction materials known."

It's a compelling vision, and one that will require the combined efforts not just of architects and engineers, but also of plant biochemists, polymer chemists and experts in fluid mechanics. The ambitious five-year project aims to "fundamentally transform the way we build" and is led by Ramage from the Department of Architecture with £1.75 million funding from the Leverhulme Trust.

"There are more varieties of plants than there are of manufactured materials," added Ramage. "Although the techniques to manipulate manufactured materials are better understood, the potential to generate materials with diverse properties based on plants may be far greater."

Plants derive much of their strength from the rigid cellulose wall that surrounds each cell. What if this could be engineered

"Although the techniques to manipulate manufactured materials are better understood, the potential to generate materials with diverse properties based on plants may be far greater"

to have even greater strength, rather like reinforcing steel bars are used to improve the tensile strength of concrete?

Team member Professor Paul Dupree from the Department of Biochemistry is an expert in understanding how plant cell walls are built. Although this structure forms one of the largest biomasses on Earth, many fundamental aspects of its structure and function, and the enzymes responsible for its synthesis, have largely been a mystery. Dupree's work focuses on improving the efficiency of using plants as biofuels by determining how to release the myriad of sugars locked into the cell wall. By deciphering how to unbuild cell walls, he is also gaining understanding of how they can be built better. Ultimately, the researchers would like to understand the process enough to be able to breed or genetically engineer plants that are naturally stronger.

Meanwhile, pioneering work by Ramage and Dr Oren Scherman, in the Department of Chemistry, is looking at boosting the strength, stiffness and longevity of plant-based materials by impregnating them with polymers. Their aim is to use low-value, fast-growing species like spruce and bamboo (see panel) in tall buildings. For instance, they have shown that impregnation of spruce by soaking in methacrylate, a polymer commonly used in windscreen repair kits, can increase spruce's strength and resistance to fungal attack.

This technology could be used to construct polymer-modified wooden beams that are stronger at the ends for better connections, and stiffer in the middle for greater spans. Scherman, Ramage and Dupree will work together to understand where the polymers end up in the plant cell and what this means for improving structural properties.

And it's not just structural construction materials that the researchers have in mind. They hope to uncover a range of uses and scales of modified natural materials that improve the sustainability of the way we live, including new materials that moderate temperature and humidity in buildings.

The expertise of Professor Paul Linden from the Department of Applied Mathematics and Theoretical Physics will be crucial for this – his group develops models of the fluid flow in low-energy buildings, which will be used to optimise the mechanical and environmental properties of naturally-based building materials. The aim is to construct buildings that not only use materials that have low embodied energy but also consume as little energy as possible when they are used. "Our ideas are a step towards 'living differently'," explained Ramage. "It's a vision that can only be achieved by strong multi-disciplinary connectivity."

The research programme fuses fundamental and applied sciences, and is firmly connected with industrial applications. Team member Dr Beatrix Schlarb-Ridley, along with Dr Brenda Parker in the Department of Plant Sciences, supports companies in the East of England in taking up low-carbon solutions based on plant materials as part of the InCrops Project. The researchers hope that this interaction will provide a continuous flow of practical ideas into the project and facilitate the transfer of new technologies into industry.

"Effectively we are working from micro to mega," summed up Ramage. "We want to redesign natural materials to carry out different functions that will change the way we construct cities. This starts at the molecular level and continues to engineered solutions to sustainable living. Our work will show a way for improved natural materials that are better for people, and better for the planet."

And as the project nears completion, Ramage and colleagues aim to return to their plans for a 70-storey skyscraper made of wood, and show this time that it can work.

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High and mighty: the new bamboo

At the World Conference on Timber Engineering this August, Michael Ramage will present research on new engineering products based on bamboo, a material that has been used to construct houses for thousands of years.

As a building material, bamboo makes great sense. It's cheap, renewable, is found in areas of the world where structural timber is limited and it grows faster than wood. Little wonder then that new forms of laminated and resin-impregnated bamboo are emerging as building materials.

"Bamboo has captured the imagination of engineers and architects worldwide, but its use has been limited largely because the material shows variations in its geometry and structural properties," explained Ramage. "Full acceptance of these materials has been hindered by a lack of engineering data on which regulatory bodies can base building standards."

"Bamboo has captured the imagination of engineers and architects worldwide"

With funding from the Engineering and Physical Sciences Research Council, Ramage and colleagues have been investigating the properties of bamboo products. He has been working with the independent consultancy Cambridge Architectural Research Limited, and in collaboration with the Massachusetts Institute of Technology and the University of British Colombia.

Their preliminary results have shown that some mechanical properties were similar to those of timber (such as stiffness), but others, like tensile strength, are up to five times greater. This suggests that bamboo might even be used to replace steel eventually, as Ramage explained: "We think that with some slightly more advanced engineering we can reconstitute bamboo into shapes like the rolled steel joists, or I-beams, used in buildings. The time has come to exploit bamboo to its full potential as a durable, strong and beautiful material."

Perovskite materials are the newest contender for breaking the silicon ceiling in solar cell technology. But they don't just absorb light. Cambridge researchers have found they emit it like a laser, opening up an entirely new field of applications.

Discovered 175 years ago in Russia's mineral treasure box – the Ural Mountains – and named after the mineralogist Count Lev Aleksevich von Perovski, perovskite is fast becoming a 'rock' to be reckoned with. In 2013, the use of perovskite materials in solar cells was voted as one of the breakthroughs of the year by *Science* magazine; more recently, the *Guardian* website declared that they "are the clean tech material development to watch right now."

Perovskite is a term used to describe a group of materials that have a distinctive crystal structure of cuboid and diamond shapes. They have long been of interest for their superconducting and ferroelectric properties. But, in the past five years, it was discovered that they are also remarkably efficient at absorbing photons of light and that this can be converted into an electric current in photovoltaic solar cells.

A defining moment came in 2012, when Professors Henry Snaith at the University of Oxford and Michael Graetzel at the Federal Institute of Technology Lausanne, building on the work of Tsotomu Mayasaka from Tokyo, found that solar cells with perovskite as the active component could be made with greater than 10% power conversion efficiencies for turning the sun's rays into electrical energy. A mere two years later, Snaith increased this to 17%. For silicon-based solar cells, it's taken 20 years of research to achieve this level.

Now, researchers in Cambridge have found another property of this remarkable material – it doesn't just absorb light, it also emits it as a laser.

Led by Professor Sir Richard Friend from the Department of Physics, the researchers have been investigating how perovskites work by exciting the material with light and monitoring energy absorption at incredibly fast timescales, taking 'snapshots' a few quadrillionths of a second apart.

As PhD student Michael Price described: "This enables us to monitor directly what is happening to the electrons, which generate the current in the material – where the excitations are and how they are destroyed, essentially how fast they live and die."

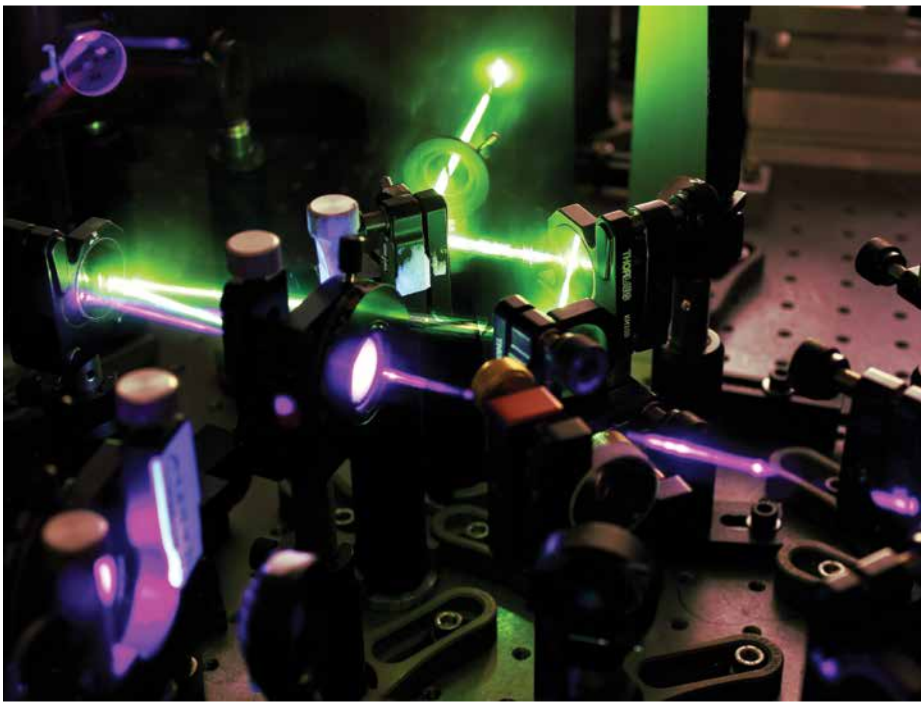
In collaboration with Snaith's group in Oxford, the scientists are using this fundamental insight to help them understand how the efficiency of perovskite-based photovoltaics might be extended yet further.

The lasing properties (published in the *Journal of Physical Chemistry Letters* in March) were discovered when Friend's team measured the photoluminescence efficiency of the material, and found that up to 70% of absorbed photons were emitted under the right conditions. This led to the idea of sandwiching a thin layer of the lead halide perovskite between two mirrors to create an optically driven laser.

"It turns out that perovskites are remarkably fluorescent materials," explained

Light in, light out: the 'rock' that breaks the rules

Image
Laser using a 'perovskite' organic metal halide material



Credit: Michael Price, Felix Deschler and Richard Friend

Friend. This is not in itself a surprise – since the early 1960s a relationship between the generation of electrical charges following light absorbtion and the process of 'recombination' of these charges to emit light has been known. "But these materials do so very efficiently," said Friend. "It's unusual in a material that is so simply and cheaply prepared."

"Mix and squirt," is how Price described the preparation process: "we make a solution of the halide perovskites and spin- coat them onto an electrode. There's no need for elaborate purification." This simple process, which the scientists say is scalable, is in contrast to the painstaking growth of crystals needed for other solar cell materials like silicon to ensure that the number of defects in the materials is kept as low as possible.

"Perovskites are cheap and abundant, they are easily fabricated and they have a high efficiency of energy conversion – these three together are the holy grail of photovoltaics, which is why there is such excitement about them at the moment," added Dr Felix Deschler.

Intriguingly, early results show that the material doesn't appear to work in the way that might be expected. "For me, the excitement is that these materials break the rules," said Friend. "Many of their properties are somewhere between those of an organic and an inorganic semiconductor. The way we make them, they should have too many chemical and structural defects to work as well as they do and yet they are as efficient as purified silicon, which is a single crystal."

Would they be better if cleaned up? "Possibly," said Friend, "but we want to have our cake and eat it. We want the efficiencies and the ease of preparation."

Defects in materials normally cause charged electrons to get 'stuck' and lose their energy. One possibility for perovskites might be that the defects don't matter because the material has the capacity to 'self-heal'.

"There's something going on... these materials have a tolerance to disorder which is unusual," explained Friend. "It's speculation, but perhaps the material can fill defects on the fly. The way the material is prepared creates a lot of free ions, and these might move around and fill up defects. Imagine a bumpy road with potholes – the ions might fill the potholes and then the electrons have a smooth ride."

A better understanding of these processes will feed into the collaboration with Snaith's group, helping the scale-up and commercial deployment of perovskite-based photovoltaics through the Oxford spin-out Oxford Photovoltaics.

Meanwhile, the Cambridge team is also pursuing the material's light-emitting properties, as Deschler explained: "It opens up a completely new field of applications. The laser industry is huge – they are used in areas that are critical for our lives, including telecommunications, medicine and industry. We think there will be applications for perovskites that extend far beyond the solar cell."

In particular, the researchers are now looking at applying the high luminescence efficiency to create light-emitting diodes. Other members in the research group have already had some very promising results in this area, which should be published soon.

> **The lasing properties were discovered when Friend's team measured the photoluminescence efficiency of the material, and found that up to 70% of absorbed photons were emitted**

The lasing properties of perovskites raise expectations for even higher solar cell efficiencies, as Friend explained: "There's a fundamental relationship between how good a material is at emitting light and how well it works in a solar cell."

The team's work is based on a programme of research on organic (i.e. carbon-containing) semiconductors that has spanned over 20 years in Friend's laboratory, most recently as part of the Winton Programme for the Physics of Sustainability, and has resulted in the development of roll-to-roll printing of photovoltaic materials, light-emitting diodes (LEDs) and printed transistors for paper displays. The techniques Friend's group has developed for characterising organic semiconductors are now being deployed on the mostly inorganic perovskite materials.

The current focus is on identifying the fundamental mechanisms that are at play when photons of light raise electrons in the material to higher energy states, and on looking at precisely how and where energy losses occur – an understanding of which will be crucial to maximising the efficiency of these light-harvesting solar cells.

"This feels like it's the dawn of a new field," said Friend. "So far we've looked at the materials as they are. The question now is how good will they be?"

www.winton.phy.cam.ac.uk

Left to right
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The atomic building site

> The ability to control atoms as if they were billiard balls is required to make the next generation of advanced materials possible

The ability to design, control and build new materials at the level of individual atoms could open up a whole new world of electronic devices.

Making a perfectly flat layer of billiard balls is fairly straightforward. Doing the same thing with atoms is rather more difficult. But as we demand more of materials, the ability to control atoms as if they were billiard balls is required to make the next generation of advanced materials possible.

Researchers in Cambridge are bringing these 'made-to-measure' materials one step closer to practical applications, and soon they will do so at unprecedented levels, thanks to a new pulsed laser deposition (PLD) system – unique in the UK – that allows for atom-by-atom design and growth.

Oxides are prime candidates for making these new applications possible. Complex oxides – compounds of oxygen and one or more metallic elements – potentially have new properties that surpass those of silicon-based electronics. These make them ideal for next-generation computing devices that process vast amounts of data in an energy-efficient way.

However, it's extremely difficult to control the growth of complex oxides at the atomic level. To achieve this, new methods of laying down atoms need to be found, and any defects in the materials need to be minimised or eliminated.

Defects influence the electronic properties of a material. In conventional electronic devices, information is carried via the charge or spin on electrons, so anything interfering with the electrons will affect the material's performance. Atoms located in the wrong place or missing entirely can snare electrons like a mouse in a trap. The number of defects that can be tolerated varies depending on the application. Semiconductors, for instance, need to be as close to perfection as possible: the maximum amount of imperfection that can be tolerated is roughly equivalent to a pinhead on a football pitch.

"Designing and growing new materials at the atomic scale are not yet 'made-to-measure' processes," said Professor Judith Driscoll of the Department of Materials Science and Metallurgy, who specialises in fine-tuning the properties of oxides for applications in energy, low-energy electronics and photovoltaics. The properties of oxide materials can be manipulated by changing the bond lengths or angles between atoms, but cost-effectively designing them to be as close to perfect as possible is not easy.

"Over the past 15 years, we've made huge advances with making materials perfect at nanometre-length scales, but we still can't easily understand things going on at the atomic scale. You assume that things are perfect, but in reality they are not, and you don't know by how much – you can only infer it from indirect measurements. To make really perfect structures, you have to be able to control the number of atoms being deposited and to stop at the exact point that a single complete layer has been grown."

Most metal oxides are grown using thin-film deposition techniques, where atomic layers are built one on top of the other on a substrate. Thin-film techniques are used by several Cambridge research groups who are interested in the physics and chemistry of functional materials, and how they can be manipulated. For instance, in the Department of Physics, researchers are using these techniques to explore the quantum properties of semiconductors. In Materials Science, Professor Neil Mathur's group uses thin films to study the electrical and magnetic properties of materials, for example attempting to control either their temperature or their magnetism through voltage; and Professor Mark Blamire's group is using them to create new kinds of magnetic and superconducting devices.

While thin-film techniques such as 'sputtering' (eroding material from a source onto a substrate) have been vital in getting advanced materials such as metal oxides to their current state, they do not provide either the level of control that's needed to see them used in practical applications nor the capabilities to make them at scale, as Blamire explained: "Sputtering is a very flexible and accurate technique for many types of metals, but it is not particularly well-suited to single-crystal oxide thin films. We have invested heavily in pulsed laser deposition, but the thickness control and the range of materials which can be grown is still limited."

Now, Driscoll, along with colleagues in Materials Science and the Department of Physics, has secured funding from the University and the Engineering and Physical Sciences Research Council for state-of-the-art new PLD equipment that will make 'made-to-measure' materials possible. The new system uses advanced PLD with reflective high-energy electron diffraction to control growth rate and produce single atomic layers with a minimum of defects.

The technique will give researchers the capability to measure thin-film thicknesses with extremely high levels of accuracy – down to less than one nanometre in thickness – as well as the ability to perform *in situ* chemical analysis to ensure the materials and the surfaces they are creating have the intended chemical and electronic structures.

"In addition to helping us build really useful things from oxides, this new technology will help us to discover and explore the properties of new materials," added Driscoll. "It will take some long-term thinking to see them transition to practical applications, but once we achieve control over these materials at the atomic scale, the practical applications will follow. We believe that such oxides could really revolutionise electronics."

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Manufacturing with ultra precision

Developing advanced materials is only part of the journey that leads to new technologies. Manufacturing companies also need to make them with ultra precision.

The next generation of smart phones might monitor your heart rate, measure the alcohol in your blood or give you a complete checkup by analysing the chemistry of your sweat. These 'personal assistants' will have an array of embedded miniature sensors and processors derived from the latest breakthroughs in microelectromechanical systems technology.

But to make devices like these requires extraordinary levels of precision – the ability to manufacture intricate features that are smaller than 100 nanometres.

Diagnostic smartphones are just one example of the new kinds of products that are going to need ultra precision manufacturing. The emergence of polymer or carbon-based materials like graphene is driving research and development in areas such as the production of lower cost, more-efficient solar cells and 'printed electronics' that can be used for flexible display screens and smart labelling.

"For these devices to become reality, companies are going to need a whole new set of production capabilities," explained Professor Bill O'Neill at Cambridge's Institute for Manufacturing (IfM), in the Department of Engineering. The ultra precision research his team carry out at the IfM is focused on building these kinds of machines and developing the associated systems and processes that can make things at nano levels of precision.

In 2011, the Engineering and Physical Sciences Research Council awarded £6 million to the Centre for Innovative Manufacturing in Ultra Precision, a joint venture between the University of Cambridge and Cranfield University.

"Cranfield has decades of experience of designing machines, including some of the most precise machine tools in the world," he said. "By virtue of the extensive materials research taking place across the University, we have experience of working with the new generation of unconventional semiconductor materials. The partnership with Cranfield coupled with the cross-Cambridge collaborations creates a very strong team with the potential to transform the way we think about and make the next generation of products.

"The endgame for us is to provide industry with a wide range of experts in various disciplines that are centred around the design, development and production of ultra precision products and processes."

Feature article available online

Extreme sleepover: All aboard the floating science factory

Deep sea sediment cores – they're cold, they're muddy, and they're revealing 30,000 years of climate history – as PhD student Julia Gottschalk reports from her voyage aboard the *James Cook* research ship last summer.

The vast and enigmatic ocean covers about three quarters of the Earth, yet the information we have from its depths is comparable with the distribution and size of the holes on a golf course.

I am waking up at sea. It is 7.50am. In 10 minutes, my daily shift on our oceanographic expedition will start and I had better be on deck.

The *James Cook*, a British Royal Research Ship operated by the Natural Environment Research Council and the National Oceanographic Centre, left Southampton about three weeks ago. Aboard with me are 26 scientists from Cambridge, Zurich, Lisbon, Barcelona and Bremen, plus crew. After rough seas in the Bay of Biscay, an escort of dolphins

and a stop in Spain to load geophysical equipment, we have made our way to our working area – the continental margin off Portugal.

It's an extraordinary region for the study of past ocean chemistry and climate dynamics. Sea floor sediments capture the ocean's history because the nature and the chemical composition of particles settling to the sea floor varied as the atmospheric and oceanic circulation changed over time.

The pioneering work of Cambridge palaeoclimatologist Professor Sir Nicholas Shackleton showed that these sediments record climate signals from the North Atlantic and the Southern Ocean. The discovery of interhemispherically linked climate changes recorded by tiny microfossils the size of sugar grains preserved in sea floor sediments at a single site was a milestone in the field.

I'm here as part of my PhD research with Dr Luke Skinner and Professor David Hodell, and our mission is to continue Shackleton's legacy by studying climate history further back in time and in more detail.

The geophysical-acoustic imaging of Iberian margin sediment below the sea floor, one of the objectives of this voyage, was finished several days ago and sediment coring operations have started – or as our geophysicist colleagues call it – playing with mud!

It is very hard to get up from my berth. A quick look out of the porthole... it doesn't look like a washing machine, it will be a calm day at sea. Making my way to the ship's working deck and jumping into my already mud-covered overall, I discuss with Natalia from the 'four-to-eight' shift what I can expect during my shift.

Stepping out onto the deck, I see a bright-blue sea, glittering like silk as the sun begins to rise... and the arrival of the box corer, a 40 by 40 cm steel box that carves into the sediment to sample a chunk of sea floor mud and ideally some bottom water from just above the sea floor. As we look at the newly retrieved box core we are impressed by the chunk of original sea floor that rose from 4 km below the point we are standing now. Charly, my shift-mate, and I invent names for the tube worms and some gastropods we see, and then start to subsample and scrape off the surface of mud.

I see a bright-blue sea, glittering like silk as the sun begins to rise... and the arrival of the box corer

The topmost sediment reflects modern conditions and can therefore be used for calibrations. The sediments are extremely cold. It's 2°C at that depth, quite a contrast to the air temperature of 23°C today.

We hand subsamples over to the micro-sensor measurement and water chemistry groups who work in specialised labs on the ship while we continue sampling for later analyses. Other scientists prepare new water sample measurements and add chemicals to the sampled sediments, the deck crew prepares the deployment of the next coring device, the bridge plans the route to the next station, the geophysicists analyse data, and the kitchen crew prepares another delicious meal… we are a floating science factory at 10°W, 37.5°N on the Atlantic Ocean.

The digital screen showing data from the winch indicates 10 minutes to the retrieval of the kasten corer. This long, steel

> **Bolt by bolt, we open the lid of the barrel – the moment of revelation**

container penetrates the sediment to much greater depths than the box corer. The deck crew lay the kasten corer horizontally down on the deck for us with a crane and after disassembling the 6-metre-long core barrel, bolt by bolt, we open the lid of the barrel – the moment of revelation. How much has been sampled? What does the sediment look like?

We get a beautiful view of 4 m of original Iberian margin sediments – about 30,000 years of climate history. The changes in colour document the oxygen-rich, bright sediment full of tiny fossils of marine plankton that thrived in the oceans of the past 10,000 years. We even find a fossil coral.

Sediments formed during the last ice age, when the oceans were much cooler, are usually much darker, which suggests that ocean circulation and ecosystems were very different. Everybody is excited about the new samples. Many hands are needed to process the bulky kasten core but this will yield enough study material for a range of different analyses.

By the end of our five-week-long cruise, we will have sampled 166 m of ocean sediment, analysed 1,000 water samples, seismically imaged the sea floor along a track 755 km long and studied 47,000 litres of ocean water. The ocean remains big and mysterious but we are getting closer to its secrets day by day.

Audio slideshow available online

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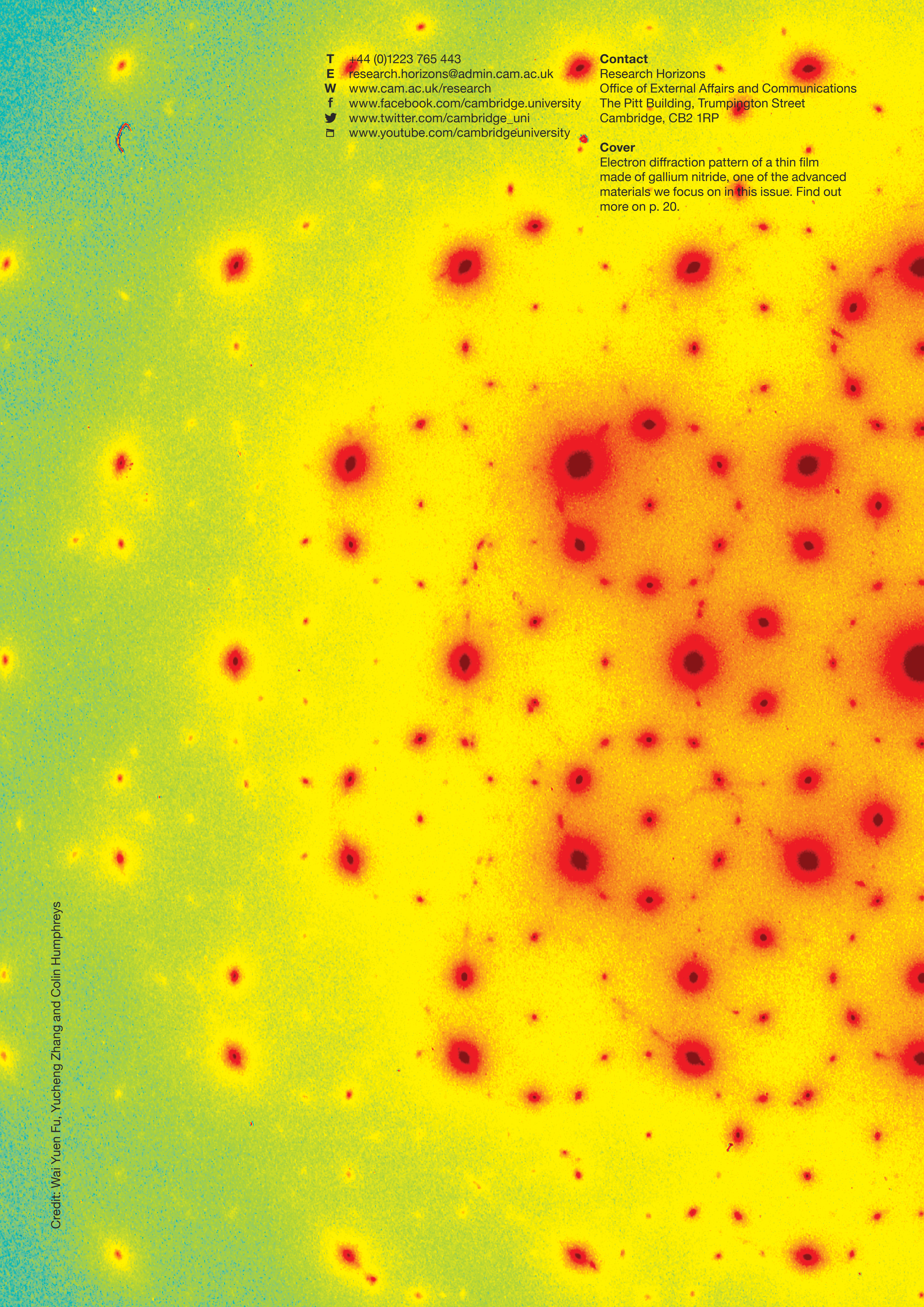

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Cover
Electron diffraction pattern of a thin film made of gallium nitride, one of the advanced materials we focus on in this issue. Find out more on p. 20.

Credit: Wai Yuen Fu, Yucheng Zhang and Colin Humphreys