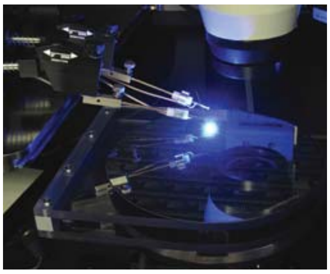
WATER PURIFICATION

The earth's atmosphere prevents deep ultra-violet radiation from reaching us, so life on earth has developed in the absence of deep-UV light, and it has no defence against it. Deep-UV light damages the nucleic acid in both DNA and



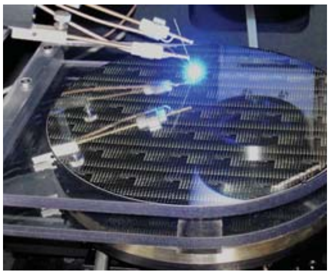
RNA and stops all bacteria and viruses from reproducing: effectively killing them. By adding aluminium to gallium nitride we can produce LEDs emitting deep-UV light. At present the intensity of the light is not sufficient to purify flowing water, so more research is needed. However, there is the clear potential to save literally millions of lives in the developing world by using this gallium nitride technology, which

... Optimised LED lighting in schools ...

could be powered by solar cells. It would also be more efficient than chlorination in the developed world.

SECURE COMMUNICATIONS AND LIFI

We are researching gallium nitride single photon sources to create pairs of entangled photons for totally secure communications. For example, mobile phone conversations could then be totally secure. In addition, in about five years time WiFi radio frequency bands will become saturated. We are



researching transmitting the same information using light from LEDs, thus overcoming the potential WiFi crisis.

CONCLUSIONS

Gallium nitride is a key material for saving 25% of electricity and carbon emissions. It can also save millions of lives, provide secure communications and augment WiFi. It can improve productivity at work and in schools. It can help UK

... stops all bacteria and viruses from reproducing ...

manufacturing and job creation. Optimised LED lighting can improve the health of us all. The UK is at the forefront of this amazing new material.

NANOTECHNOLOGY

Meeting of the Parliamentary and Scientific Committee on Tuesday 14th July

NANOTECHNOLOGY – what is it and what is it for?

Professor Andrew Fisher
University College London

Professor Milo Shaffer
Imperial College London

Co-Directors, London Centre for Nanotechnology

Nanotechnology is driven by a collision of science and techniques drawn from different disciplines, which has uncovered new fundamental behaviours of matter and new opportunities for practical applications. Modern semiconductor integrated circuits are carved, "top-down", at increasingly short length scales, underpinning the continuous improvement in electronics over recent decades ('Moore's law'). At the same time, chemists have learnt how to build increasingly large, well-defined structures from "the bottom up". These worlds intersect at the nanoscale, where dimensions are measured in nanometres (billionths of a metre); it is the same lengthscale on which much of the complex machinery of living systems operates. Within this range, the physical laws governing the behaviour of matter begin to switch from classical to quantum mechanical, and become subtly dependent on size. The concepts, knowledge, and tools from different disciplines, including electronic engineering, materials science, chemistry, physics, biochemistry, and medicine are being exchanged and developed, creating new opportunities in which science and technology are synergistic: new science leads to new technologies, which in turn enable further scientific developments.

THE LONDON CENTRE FOR NANOTECHNOLOGY

Almost ten years ago UCL and Imperial College London decided to create a joint London Centre for Nanotechnology (LCN) using funding from the HEFCE Science Research Infrastructure Fund, recognizing the very widespread importance that now attaches to the ability to control matter in the nanometre range. The LCN concept involves making available to the widest possible range of researchers a full set of tools for making and characterizing nanostructures, enabling them to carry out leading fundamental research and to target applications in information technology, healthcare and the environment.

By combining two of the UK's strongest research universities the LCN provides a large, high-quality and exceptionally diverse research community that can take full advantage of these nanoscale tools, which have become pervasive in current science and technology. The institutions have great strengths across the physical and biological sciences, as well as in engineering, and in biomedicine – the location in central London, close to Europe's largest concentration of specialist medical care, gives it unmatched opportunities for research with the healthcare sector and for technology transfer. This large research community makes it possible to invest in a broader range of equipment than would be possible for for a single university.

LOCAL VERSUS NATIONAL FACILITIES

An important part of the LCN philosophy is that nanoscale fabrication tools should be available as locally as possible, so that they can become part of the everyday research programme for the participating groups. Even in London traffic, UCL and Imperial are close enough that it is easy to travel from one to the other!

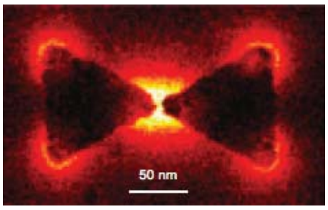
Other facilities involve major infrastructure that cannot be provided even in a multi-institution collaboration such as the LCN. Particularly important are neutron and X-ray scattering, which involve wavelengths which match the separation between atoms. This infrastructure is best provided as a national facility, and LCN researchers are large users of the UK's ISIS neutron facility and Diamond X-ray synchrotron.

The LCN team also works closely with a range of other interdisciplinary initiatives in London, including the Thomas Young Centre for the Theory and Simulation of Materials, a leading platform for advancing the performance of materials, and the Centre for Plastic Electronics, focused on the development of cheap, large area devices such as solar cells and displays.

NANOSCALE TOOLS

Core fabrication facilities in nanotechnology rely on both the high performance clean room environments needed for detailed photo- and electron lithography, scribing nanoscale patterns on the surface of a material, and the wet labs required for (bio)chemical synthesis and analysis. Some of the most interesting opportunities arise from the integration of these approaches, requiring adjacent coordinated facilities. Characterization of the resulting structures has often been a limiting step. The LCN, with support from the Engineering and Physical Sciences Research Council (EPSRC), installed the UK's first Titan monochromated, aberration-corrected electron microscope, giving access to an order of magnitude improvement in resolution. Over the last decade, revolutionary developments in electron microscopy have allowed imaging even of individual atoms. In addition, electron spectroscopy can reveal the chemical identity of the atoms or resolve functional properties of nanostructures.

Similarly, again supported by EPSRC, the LCN installed the UK's first neon ion microscope, providing unprecedented combined ability to mill



Direct imaging of the plasmon resonance associated with a metal "nano-bow tie", using the Titan electron microscope; such structures are useful for manipulating light on scales shorter than its own wavelength, for sensing, high resolution imaging, and photonics, courtesy of Prof Stefan Maier

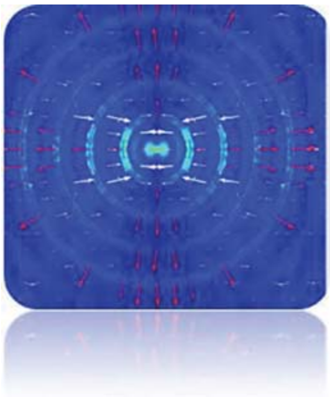


Image of a 20 nm nanopore ion-milled into a membrane, designed to assist the sequencing of individual strands of DNA. The concentric 'bull-eye' pattern concentrates light to control the temperature at the pore. Courtesy Dr Josh Edel.

nanostructures and to image the results.

Future infrastructure developments may target emerging themes in automated/instrumented robotic experimentation, three (or more) dimensional imaging/visualisation at different lengthscales, and environmental characterisation under "realistic" conditions. It is essential to continue to invest in state of the art equipment, to remain internationally competitive, and to exploit the latest technological opportunities.

EXAMPLES

Nanoscience and nanotechnology now play an integral role in many fields, and in many potential applications. These range from improved high performance electronics, aiming to beat the limitations of Moore's law, to the development of more environmentally-friendly chemical processes and energy sources, and the advancement of new therapies based on nanomedicine. A few examples follow.

Catalysts

Catalysts are now playing an increasingly important role in the removal of pollutants from vehicle exhausts in catalytic convertors. The active components of many catalysts are nanoparticles, and it is becoming clear that their effectiveness depends critically on how much the atoms are 'strained' or distorted from their ideal geometries. It has been difficult or impossible to determine this strain until recently but now Prof Ian Robinson, in a joint project with Johnson Matthey, has shown how the information from scattered X-rays can be cleverly combined to produce a strain image of a single particle. An alternative strategy includes nanoparticles catalysts within the fuel itself to improve fuel efficiency and reduce soot formation; the effect of such particles on the vehicle exhaust and their potential impact on human health is being studied using advanced imaging tools, such as Titan, in a collaborative project with the US Environmental Protection Agency, led by Prof Terry Tetley.

Scanning probes

One of the most powerful tools in probing the nanoscale world has been the scanning

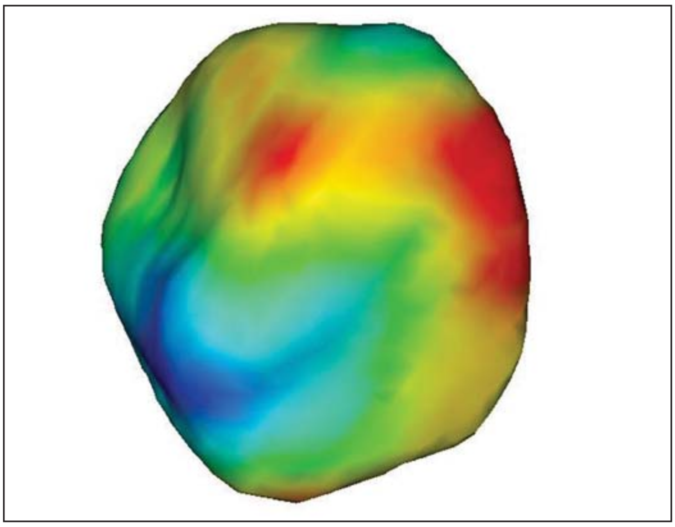
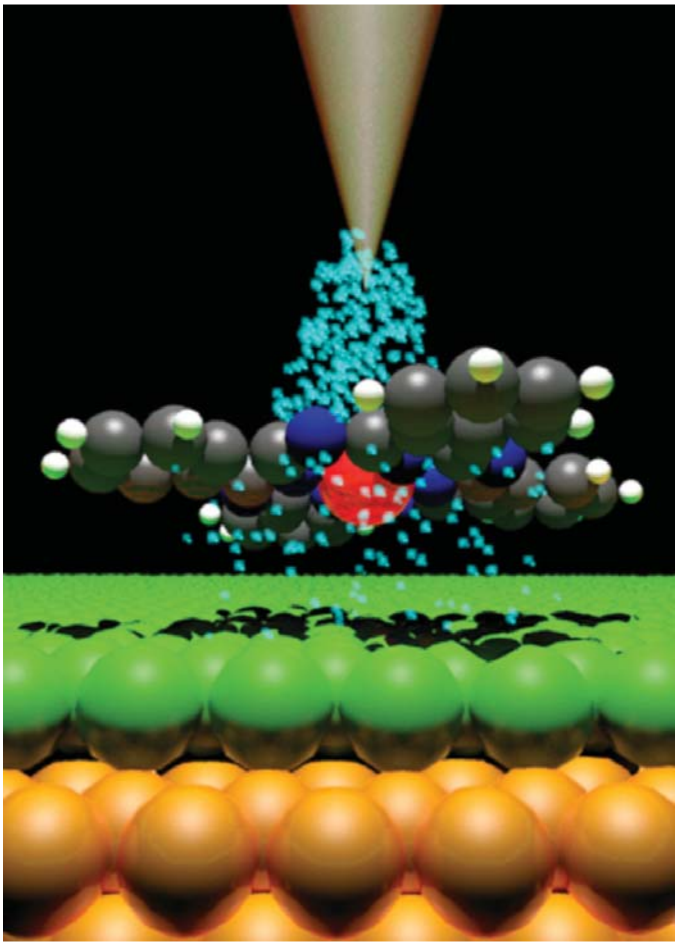


Image of an individual nanoparticle, the colour coding the strain of the atoms. Courtesy Professor Ian Robinson and Rachel O'Malley (Johnson Matthey).

probe microscope, in which a microscopic tip 'feels' the structure under investigation as it scans across it. LCN researchers have been particularly prominent in developing this technique; in one notable example Dr Bart Hoogenboom and his colleagues were able to image "nanodrills" at work, built by individual proteins that bacteria produce to kill living cells That advance relied on pushing the technique to detect the weak forces that operate in soft biological environment. Another variant involves detecting the electrical current through an atom or molecule, rather than the force. Using this approach, Dr Cyrus Hirjibehedin and his colleagues have been able to demonstrate a single-molecule magnetic sensor in which the electrical current is up to 60 times more sensitive to a magnetic field than had previously been expected.

Nanoscale devices for quantum technologies

Ultimately, we would like to be able to create devices that function entirely according to the microscopic laws of quantum mechanics. It has been known for many years that these laws determine the behaviour of individual atoms and molecules, but whole devices operating on quantum principles have new properties – they can process information in new ways, and can perform some important tasks (for example, breaking large whole numbers into their factors – a critical task in attacking the security of present-day cryptography) much more efficiently than any 'normal' computer. The UK National Quantum Technology programme has recently started some important projects to bring quantum technologies to short-term application, but in the long term many researchers believe that the scalability possessed by nanoscale solid-state systems will win out over competing approaches. In this context, an especially important recent demonstration came from the LCN's Prof John Morton and colleagues, who showed that fragile quantum information can be preserved in silicon (the same material used in conventional electronics) for unprecedentedly long times from seconds to several hours



Schematic of a magnetic molecule (centre) on a surface. The magnetization of the molecule interacts with local magnetic fields and also with electrons emitted by the scanning probe microscope tip, thereby affecting the current and forming a sensitive magnetic field sensor. Courtesy Dr Cyrus Hirjibehedin, image by Tobias Gill

i-sense: Early detection of infectious disease

Globally, infectious diseases such as influenza, Ebola, MRSA and HIV rank among the gravest threats to human health, alongside global warming and terrorism. Nanotechnology offers the possibility of sensitive and specific, cheap, disposable diagnostics that will widen access to testing in the community and the developing world. At the LCN, Professor Rachel McKendry directs i-sense, the EPSRC Interdisciplinary Research Collaboration in Early Warning Sensing Systems for Infectious Diseases. This multi-partner centre aims to detect disease much earlier than before by linking web data, such as social media posts, with nano-enabled, mobile phone-connected diagnostic tests. Patients will benefit by gaining faster access to treatment, the NHS and global healthcare providers will benefit from targeted care and antibiotic stewardship, and populations will benefit from the reduced spread of infection.

THE NANOTECHNOLOGY WORKFORCE

What kinds of people are driving this work forward? A quick survey of the current LCN workforce reveals representatives from France, Italy, Germany, Sweden, The Netherlands, Israel, Russia, India, Japan, China and Kenya as well as the United States, Canada, Australia and of course the UK. This mix is not atypical of fast-moving areas of science and technology, but underlines how important it is for UK universities to be able to appoint people with the very best skills internationally, in order to compete in the global

Image illustrating the concept of the i-sense project. Low-cost diagnostic tests, relying on nanotechnology and integrated with mobile phones, form part of a multi-scale approach including monitoring of web posts and social media. Courtesy of Prof Rachel McKendry and Kailey Nolan.

marketplace for ideas. It is essential to be able to access the best talent at every level from students, through researchers, to experienced academics and industrialists. Policies that encourage, for example, PhD students to stay in the UK and start new businesses here exploiting their knowledge, rather than insisting that they leave the country immediately, would be beneficial.

For such an international field it is also especially important to ensure that the UK is able to take part in international collaborative research projects. In particular, the UK benefits disproportionately from EU funding; any withdrawal from the EU science framework would have a devastating impact on UK science, both in loss of revenue and loss of opportunities for international collaborations, most of which also involve companies or end-users. Many of the schemes (such as the European Research Council Fellowships) bring significant international prestige as well as opportunity, which helps the UK to attract the best talent.

SAFETY

As nanotechnology moves forward into commercialization, it is critical to ensure that potential impacts on human health and the environment are taken into account. The field in the UK benefited from a landmark Royal Society and Royal Academy of Engineering report in 2004 entitled *Nanoscience and nanotechnologies: opportunities and uncertainties*, which provided an early and widely respected analysis. It served both to promote an awareness of safety and ethical issues within the field, and to reassure those outside it that early and somewhat sensational warnings of the risks from 'grey goo' nanotechnologies were overstated. The report concluded that many nanotechnologies do not raise any particular concerns beyond conventional industrial manufacturing, for example, when small structures are buried within larger electronic devices. The safety of the manufacturing process and the life cycle fate of the product must be considered, but conventional approaches are generally appropriate. In certain cases, however, there is a chance that discrete, engineered nanoparticles might be released, either accidentally or deliberately, leading to human or environmental exposure. In these cases, the fate of the nanoparticles must be considered carefully. Atmospheric pollution, for example by diesel soot, is one very prominent example of nanoparticle release; other nanoparticles occur in very much smaller quantities. However, the fate and influence of these particles need to be considered on a case by case basis. Considerable research to date has shown that the behaviour is very dependent on the composition, size, and use of the nanoparticles. In some cases, there is no immediate concern, while in others suitable precautions relating to exposure should be employed. Particular care will be needed in nanomedical applications, where nanomaterials are directly administered to humans, although rigorous testing can be anticipated.

THE FUTURE AND COMMERCIALIZATION

Nanostructured components will increasingly appear as crucial enabling elements integrated in complete functional systems for a wide range of applications. Improvements in cost-effective nanomanufacturing will accelerate implementation. The combination of nanostructures with other components will increasingly create "hierarchical systems" operating over a range of lengthscales. It is worth highlighting that biology is especially adept at building functional materials specified at every possible lengthscale. We, on the other hand, are good at atomic scale manipulation through chemistry, and micron-scale manipulation through engineering, but very unskilled in the intervening nanoscale. Famously, Richard Feynman announced that there was "plenty of room at the bottom", but we may now consider that there is still "plenty of room in the middle" to integrate top-down and bottom-up approaches, to deliver new technologies with economic and societal benefits.

New materials and manufacturing technologies typically have long development cycles. Initial enthusiasm sometimes wanes too quickly for the development of real technologies, and many opportunities are lost in "the valley of death" between initial promise and ultimate delivery. Unfortunately, the UK generally has a poor record in making the most of its own intellectual achievements. It is critical that government, industrial, and venture-driven R&D investment takes a sufficiently long term view that the new opportunities are manifested within the UK.

Transforming our lives with Nanotechnology in safe and responsible way

Professor Alex Orlov
Assistant Professor of Material Science and Engineering, State University of New York, Stony Brook

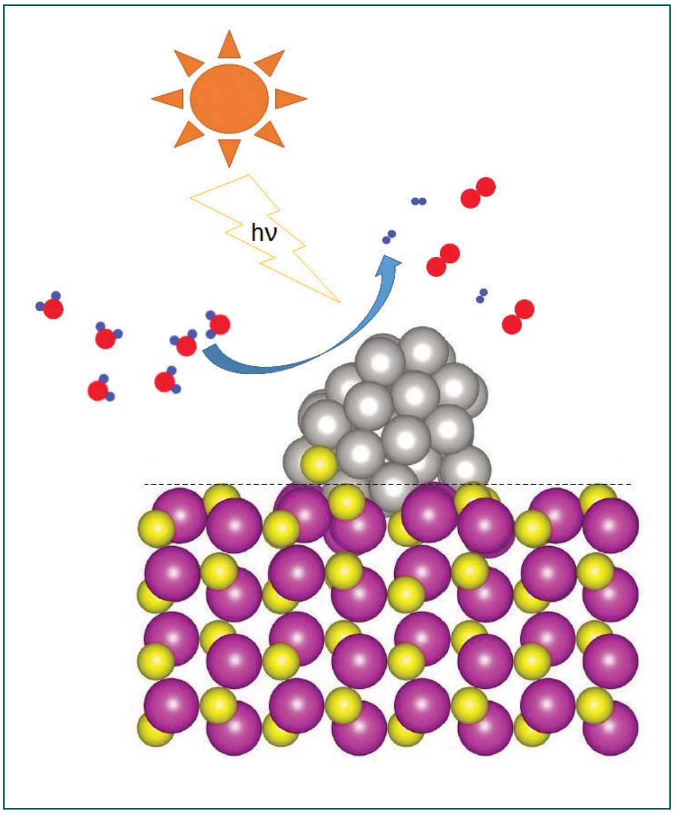
Nanotechnology is very exciting field. From revolutionizing medical applications to producing the most efficient electronic devices, it is already transforming our daily lives.

In the US there has been very little controversy related to funding of this emerging field. The US National Nanotechnology Initiative (NNI), a coordinating organization for 20 Federal departments and independent Agencies, was given over $21 billion since its inception in 2001. The budget request for the coming year was $1.5 billion, in line with the previous budget proposals. This initiative has gained strong support from three Presidential administrations, resulting in technological advances in solar energy conversion, nanomanufacturing and sensors. It is not a coincidence that the technological competitiveness of the US economy is strongly linked to research and commercialization of nanotechnology.

... NNI has recognized the importance of blue sky research ...

The late John Marburger, Chief Science Adviser to President Bush, stated that NNI was one of the least controversial sciences and technology programs for budget appropriations. This is not surprising, given that this initiative facilitates investment into research infrastructure, education and applied/fundamental research. It has enabled many disciplines, ranging from medicine to electronics, to develop new science and commercial applications. The NNI has recognized the importance of blue sky research, with almost 35% of the budget dedicated to such fundamental research. The Policy makers in the US have recognized that skewing research funding too much towards applied research can potentially undermine all the future breakthroughs enabling commercial applications of nanotechnology.

Despite the enormous potential for nanotechnology to improve our wellbeing, there are still questions about safety of nanoparticles to humans and the environment. In relation to safety there are two aspects to consider. Firstly, contrary to popular beliefs, nanotechnology can solve many environmental problems. For example, nanoparticles can reduce environmental contamination, produce energy in a cleaner way

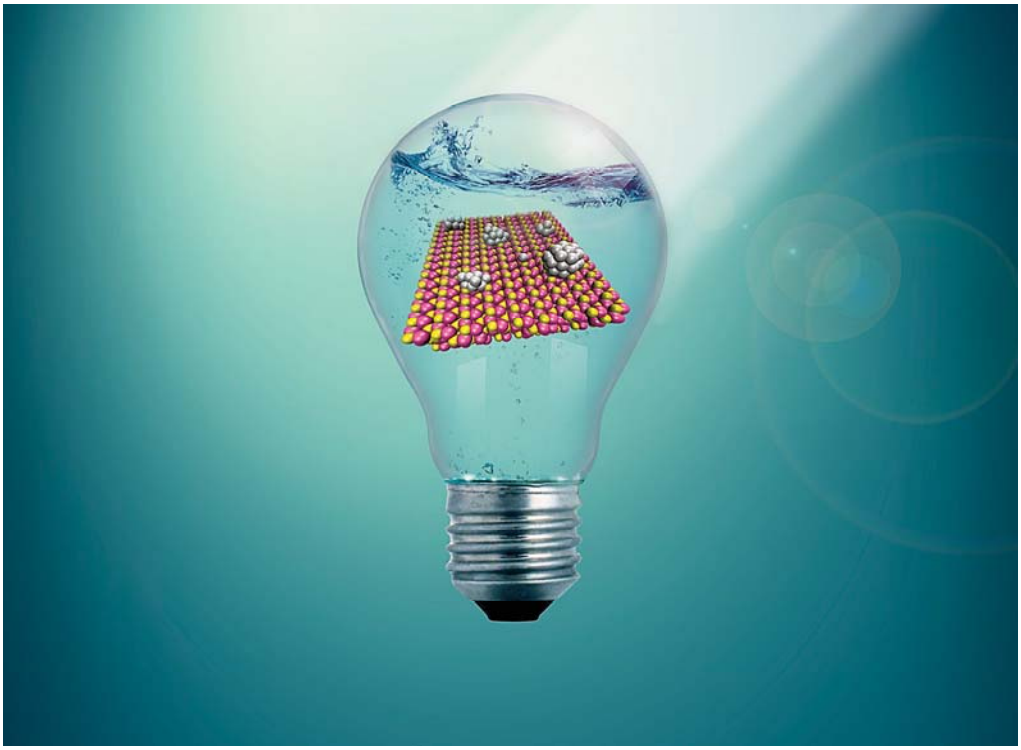


Reproduced from Orlov, A. Catal. Sci. Technol., 2015, 5, 2504. with permission from the the Royal Society of Chemistry and make conventional materials less harmful. In 2009 the OECD organized one of the first meetings on the topic, to offer an alternative view to toxicology driven perception of nanomaterials. This meeting offered a glimpse of the emerging field, called environmental nanotechnology, aimed at improving human health and the environment. Nanoparticles can also enhance ecological health indirectly by facilitating clean energy production. We have created a new generation of nanoparticles, which can produce clean source of energy from water using sunlight. The product of this reaction, hydrogen gas, can then be used to power fuel cells to produce electricity. We have also demonstrated how to use nanoparticles to clean water and air pollution, both on a small scale and on urban scale. This approach is currently being utilized in a recent commercial development by the US company called PURETi, which coats urban surfaces with self-cleaning and air purifying nano-coatings. In addition to nanoparticles, nanotechnology can also create such nanostructures as nanopores in membranes. These membranes are already saving millions of lives by delivering clean drinking water.

The second aspect of safety of nanoparticles is as following. Despite the promise of nanotechnology it is foolish to dismiss toxicity aspects. There are credible scientific reports on toxicity of nanoparticles. In fact the UK Government has a long standing Hazardous Substances Advisory Committee (HSAC) advising DEFRA on toxicity aspects of nanotechnology.

Being a member of this committee for almost seven years gave me a number of unique insights into the interdisciplinary aspects of the safety nanoparticles. One of the most important nuggets, which came out of numerous discussions at this committee, was that scientists working on applications of nanotechnology should collaborate with toxicologists, economists, environmental and social scientists. All these disciplines are incredibly important for conducting risk assessment of nanotechnology and for communicating these assessments to general public and policy makers. Whereas scientists and engineers always try to quantify risk factors, given the incomplete information available for most of new nanomaterials, it is often a challenging task. Finding pathways to incorporate qualitative information and accounting for such externalities as public perception and regulation is a daunting task for traditionally trained scientists and engineers working in academic environment. Transcending interdisciplinary boundaries is the only way to advance nanotechnology without harming public and environment.

... the safe development of nanotechnology will bring multiple benefits for all. ...



It can be argued that the toxicity of some nanomaterials does not necessarily mean that they have to be removed from the market. Environmental health professionals know that even the most hazardous materials present zero risks if we are not exposed to them. This concept can be used to guide new product development, whereby exposure to potentially hazardous materials can be eliminated during production, use and disposal of nanomaterials containing products. However, if existing manufacturing practices do not provide adequate protection, they have to be changed or the product has to be redesigned. If nano-enabled products are designed responsibly, it is possible to reduce risks associated with exposure to nanoparticles to negligible levels while taking advantage of their extraordinary properties. We have demonstrated a new approach to evaluation of safety of products containing carbon nanotubes. It is often assumed that nanoparticles encapsulated in polymers are safe. We demonstrated that under certain conditions this assumption might not be true. In fact there are some scenarios of these materials' exposure to sunlight, moisture and abrasion where carbon nanotubes might become detached from the polymers holding them inside. Given numerous reports of toxicity of carbon nanotubes the question then becomes whether to remove these from the market or to reformulate them to improve their safety. Recent work offered several pathways of making nanomaterials more stable and thereby safer to use. The first pathway is to substitute more harmful nanomaterials with the less harmful one. The second pathway is to redesign the entire nanomaterials containing product to make it more resilient towards environmental degradation. In case of polymers this can be achieved by adding various UV stabilizers and by making carbon nanotubes more compatible with polymer matrices.

We can be certain that the ingenuity of researchers in this area will ensure that the safe development of nanotechnology will bring multiple benefits for all.