Smart Materials: From Self-Assembly to Sensors

4th CAMatNet Symposium

Organisers: Dr Rachel Evans and Dr Sohini Kar-Naryan
Department of Materials Science and Metallurgy

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Venue: Lecture Theatre 1, Department of Chemical Engineering and Biotechnology

TALK ABSTRACTS

Sponsors:

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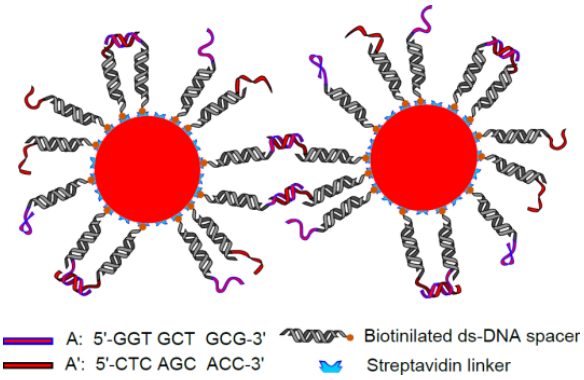
Designing Disorder Using DNA-Functionalized Colloids

Lorenzo Di Michele, Francesco Varrato, Giuseppe Foffi, and Erika Eiser
Department of Physics

Understanding and controlling the properties of amorphous materials is essential in the design of new materials. Among different amorphous structures, colloidal gels play an important role in a number of applications. We use the short-ranged attractive interactions between colloids provided by selective DNA bonding to build ramified amorphous space-spanning structures that can sustain mechanical stress. [1] The mechanism of aggregation in our system occurs through arrested demixing in binary colloidal mixtures. This leads to the formation of bigels - a new class of materials. We obtain these materials by end-grafting highly specific single-stranded (ss) DNA. As ssDNA can only bind to its complementary counterpart, we can design new colloid-colloid binding rules. Here, we present two types of amorphous gels: Two inter-percolating but independent colloidal gels which we call bigels (Figure), and a single colloidal gel subsequently coated with a single layer of a different type of colloid. Later we call coaxially coated colloidal gels. [2]

I will discuss both the structural analysis and the mechanical properties of such systems and how the same concepts can be transferred to other systems to develop new types of battery and disordered photonic materials. [3-5]



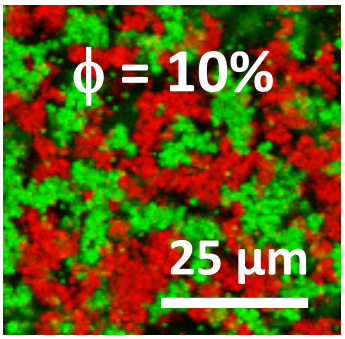


Figure: (Left) Carton of the typical colloid surfaces bound with DNA. The double strands are used a spacers, and the sticky overhangs are designed such that A and A' cannot bind to B or B'. The polymer strands in between are used to tune strength of the intra-colloidal bonds. (Right) Snapshot from a demixed bigel.[1,2]

[1] F Varrato, L DI Michele, M Belushkin, N Dorsaz, SH Nathan, E Eiser, G Foffi, *PNAS*, doi: 10.1073/pnas.1214971109 (2012).
[2] L Di Michele, F Varrato, J Kotar, SH Nathan, G Foffi, E Eiser, *Nature Comms*, DOI: 10.1038 (2013).
[3] L Di Michele, D Fiocco, F Varrato, S Sastry, E Eiser, G Foffi, *Soft Matter*, DOI: 10.1039/C3SM52558A (2014).
[4] Z Ruff, SH Nathan, RR Unwin, M Zupkauskas, D Joshi, GPC Salmond, CP Grey, E Eiser *Faraday Discussions*, **186**, 473-488 (2016)
[5] Z Ruff, CP Gray & E Eiser *Phys. Chem. Chem. Phys.* **20**, 467 (2018)

Complex and Responsive Systems via Subcomponent Self-Assembly

Dr Charlie McTernan

Department of Chemistry

The materials that we depend on rely upon ever-increasing structural complexity for their function. The use of chemical self-assembly as a synthetic technique can simplify materials preparation by shifting intellectual effort away from designing molecules, and towards the design of chemical systems. These systems can be capable of self-assembling (that is, forming complex architectures from simple building blocks, following pre-determined rules), allowing the expression of desired materials properties and functions. This talk will focus upon the design of self-assembly processes that can bring together simple organic molecules and first-row transition-metal ions into complex, functional structures.

Microfluidics for Biomimetic Infrastructure Materials

Dr Livia Ribeiro de Sousa

Department of Engineering

The biomimetic approach involves learning nature's design to engineer materials to solve critical challenges. Features such as self-healing and self-sensing, has been recently emerged as a promising strategy for extending the service life of concrete infrastructure. Amongst the various self-healing systems being developed, the use of microcapsules has received significant attention partly because of its ease implementation. Up to date, microcapsules for self-healing applications have been mainly manufactured using bulk emulsifications polymerisation techniques. However this methodology raises concerns regarding shell dimensions and interfacial bonding. Our research proposes the fabrication of microcapsules with tailored characteristics for mechanically triggered self-healing action in cement-based composites. For this, a microfluidic device was used to produce a double emulsion template for the formation of microcapsules, containing both aqueous and organic liquid core. In addition, a novel method has been proposed to functionalize the microcapsules' surface with hydrophilic groups in order to increase the interfacial bond with the cementitious host matrix. The core retention and their mechanical triggering of the microcapsules embedded in the cement paste were also investigated. The results demonstrated the capability of microfluidics to produce microcapsules with liquid organic core, thin shell, hydrophilic surface and appropriate fracture strength for use in mechanically triggered self-healing of cementitious materials. Future work includes the investigation of other biomimetic futures, such as the use of carbon-based nanomaterials for self-sensing infrastructure.

Bioactive Composites

Prof. Ruth Cameron

Department of Materials Science and Metallurgy

Resorbable composites made of resorbable polymers and calcium-based inorganics have significant therapeutic potential as tissue engineering scaffolds, as temporary implants including resorbable stents and as drug-loaded matrices for controlled release. However, their degradation is complex and the rate of resorption depends on multiple connected factors such as the shape and size of the devices, polymer chemistry and molecular weight, particle phase, size, volume fraction, distribution and pH dependent dissolution properties. Understanding and ultimately predicting the degradation of resorbable composites is of central importance if we are to fully unlock the promise of these materials.

This talk will consider the properties and potential of these materials and will describe computational models for their degradation, using analytic expressions to represent the interwoven phenomena present. This modelling framework, combined with a comprehensive database of quantitative degradation data mined from existing literature and from novel experiments, is generating new insights into the inter-related factors controlling performance.

Embodied Intelligence from the Bottom-Up: How Functional Soft Materials Make Robots More Intelligent

Dr Fumiya Iida

Department of Engineering

Compared to biological systems, today's robots are still suffering from being flexible and adaptive to uncertain and unstructured tasks and environments. Humans are for example capable of handling a large variety of objects even at younger ages, even if they are not known previously. In order to fill the gap of animals and machines in terms of dexterity and adaptability, we have been investigating the notions of embodied intelligence, i.e. how well-designed physical body can simplify executions of complex tasks and enhance their adaptability. With the recent advancement in the technologies of soft functional materials and additive manufacturing, we can develop complex soft structures to be integrated into robotic systems to systematically investigate such challenging problems. In this talk, I would like to introduce the research projects in our laboratory in which we attempt to develop dexterous and adaptive robotic hands,

Using Synthetic Materials to Re-Wire Natural Photosynthesis

Dr Jenny Zhang

Department of Chemistry, University of Cambridge

The ability to harness sunlight for performing large scale conversion of abundant/cheap materials to useful chemicals and fuels, in what is known as artificial photosynthesis, would pave the way for cleaner and more renewable energy sources in the future. Nature has already achieved this feat billions of years ago through photosynthesis; however, the process was evolved for survival and not efficiency. Semi-artificial photosynthesis aims to combine the strengths of materials chemistry with synthetic biology to explore novel pathways for efficient solar-to-chemical conversion, which are otherwise inaccessible to either field alone.

Here, I will describe the wiring of the water oxidation enzyme, photosystem II (PSII), to tailored high surface area electrodes, which allows the electrons extracted from the first step of photosynthesis to be harnessed for driving solar fuel conversion reactions.[1, 2] I will also show how the architecture of the electrodes can be modified to support live biofilms of the cyanobacteria, *Synechocystis sp. PCC 6803*, to access the long-lived photo-electrogenic activity of PSII *in vivo.* Lessons gained from these studies will inform the development of biophotovoltaics and bio-solar fuel conversion technologies.

References

1 Kato, M.; Zhang, J. Z.; Paul, N.; Reisner, E. *Chem. Soc. Rev.,* 2014, 43, 6485–6497

2 Zhang, J. Z.; Paul, N.; Sokol, K. P.; Romero, E.; Grondelle, R-V.; Reisner, E. *Nature Chem. Bio.* 2016, 12, 1046–1052.

3 Zhang, J. Z.; Bombelli, P.,; Sokol, K.; Fantuzzi, A.; Rutherford, A. W.; Howe, C.; Reisner, E., 2017, *J. Am. Chem. Soc.*, 2018, 140, 6-9.

Chemistry in the Age of Bio-Nano Hybrids and Sensing Devices

Dr Ljiljana Fruk

Department of Chemical Engineering and Biotechnology

Bio-nano hybrids are becoming increasingly important not only for design of optoelectronic devices and sensors, including those applied to wearable technology, but also for tissue engineering and drug delivery. In order to preserve inherent and introduce new properties, various chemical strategies have been developed to combine intrinsically different bio and nano structures into stable and functional systems.

The talk focuses on some old and some new chemistry used to encode
nanoelements with various clickable functional groups, which allows for the assembly of larger structures and biofunctionalisation of various non-bio surfaces. Special attention is given to photo-triggered click reactions, which enable programmable design and photo-encoding of different materials.

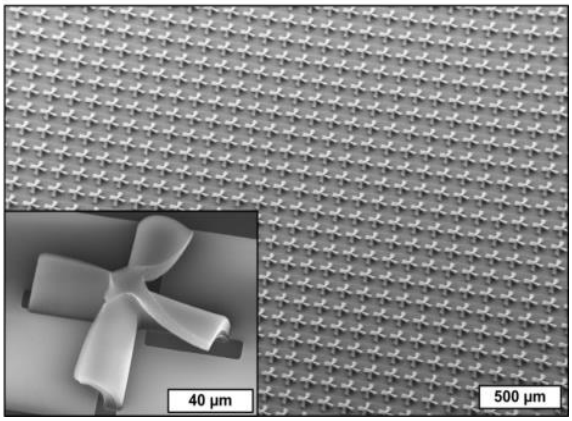
The role of chemistry in the age of bionanotechnology, sensor design and cyborg materials will be explored with the aim to prove that organic synthesis is still very much alive and kicking.

In addition, light will be shed on the importance of treating failed experiments with respect as there is an interesting story or artistic installation in every un-publishable scientific result.

Hierarchical Carbon Nanotube Structures for Sensing and Energy Storage Applications

Dr Michael de Volder

Institute for Manufacturing



Carbon nanotubes (CNTs) have been investigated intensively during the past two decades because of their excellent electrical, thermal, and mechanical properties. However, these properties are only valid for individual CNTs, whereas most CNT based devices require the assembly of tens to millions of these nanoparticles into one structure. Unfortunately, the properties of such CNT aggregates are often disappointing compared to the constituent nanoparticles. In order to leverage the full potential of CNTs for advanced material applications, it is key to control the nanotube arrangement at both the nano and microscale. In particular this talk will focus on how these structures can be used for fabricating new sensors and lithium ion batteries.

Using Optical Nanocavities to Improve Memresistive Switches

Dr Giuliana di Martino

Department of Physics

Trapping light with noble metal nanostructures overcomes the diffraction limit and can confine light to volumes typically on the order of 30 cubic nanometers. Individual atomic features inside the gap of a plasmonic nanoassembly can localize light to volumes well below 1 cubic nanometer, enabling optical experiments on the atomic scale [Science **354**, 726 (2016)]. Fabricating nanocavities in which optically active single quantum emitters are precisely positioned is crucial for building nanophotonic devices [Nano Lett. **18**, 405 (2018)].

One of the most promising contenders for ultralow-energy electronic devices is resistive switching memory (RRAM) which delivers sustainably-scalable 'neuromorphic' computing, potentially capable of reducing energy consumption in IT by >50%. Understanding the nanoscale kinetics of the switching mechanisms is needed to enable high-endurance devices – only this can unlock their integration into fast, low-energy, logic-in-memory architectures. RRAMs are currently studied by electron microscopy however this is destructive, invasive, and under drastically different conditions, so is not sufficient for developing true understandings. Using the ultra-concentration of light we recently achieved [Small **12**, 1334 (2016)], we develop innovative fast ways to study real-time movement of individual atoms that underpins this new generation of ultra-low energy memory nano-devices, thus overcoming the limitations of traditional investigation techniques and opening up new routes to sustainable future IT.

Interfacing Organic Electronic Materials with 3D Tissue Models

Dr Roisin M. Owens

Department of Chemical Engineering and Biotechnology

In vitro models of biological systems are essential for our understanding of biological systems. In many cases where animal models have failed to translate to useful data for human diseases, physiologically relevant in vitro models can bridge the gap. Many difficulties exist in interfacing complex, 3D models with sensing technology adapted for monitoring function of cells within these models. Polymeric electroactive materials and devices can bridge the gap between hard inflexible materials used for physical transducers and soft, compliant biological tissues. An additional advantage of these electronic materials is their flexibility for processing and fabrication in a wide range of formats. In this presentation, I will discuss our recent progress in adapting conducting polymer devices, including simple electrodes and transistors, to integrate with 3D cell models. We go further, by generating 3D electroactive scaffolds capable of hosting and monitoring cells.

Electrochemical actuators based on 2D MoS_2 nanosheets

Prof. Manish Chhowalla

Department of Materials Science and Metallurgy

Over the past few years we have shown that chemically exfoliated 2D transition metal dichalcogenides (TMDs) are excellent for electrochemical applications such as energy storage and catalysis. For example, electrodes from restacked TMDs exhibit excellent volumetric capacitance along with high energy and power densities in energy storage devices. In this presentation, we will describe the basic synthesis and electrochemical properties of two dimensional TMD nanosheets. We will also show that the high capacitance can be used for realizing ultra-strong electrochemical actuators. We demonstrate that films made from metallic phase MoS_2 nanosheets can generate mechanical forces that are capable of lifting masses that are > 150 times heavier than the electrode weight over several millimetres and for hundreds of cycles. The actuation performance is attributed to the high electrical conductivity of metallic 1T phase of MoS_2 nanosheets – promoting fast ion diffusion – and high elastic modulus of restacked MoS_2 layers (2 – 4 GPa).