# SYMPOSIUM BM09

Bioinspired Macromolecular Assembly and Inorganic Crystallization—From Tissue Scaffolds to Nanostructured Materials
November 26 - November 30, 2018

Symposium Organizers
Chun-Long Chen, Pacific Northwest National Laboratory
Nico Sommerdijk, Eindhoven University of Technology
Tiffany Walsh, Deakin University
Shuguang Zhang, Massachusetts Institute of Technology

Symposium Support
Pacific Northwest National Laboratory

* Invited Paper

SESSION BM09.01: Biomimetic Materials Based on Peptide Self-Assembly
Session Chairs: Chun-Long Chen and Nathaniel Rosi
Monday Morning, November 26, 2018
Sheraton, 2nd Floor, Back Bay A

**8:00 AM BM09.01.01**
**Self-Organization of Peptides in Bioinspired Vesicles—Role of Relative Concentration and Helical Separation** Akash Banerjee and Meenakshi Dutt; Chemical and Biochemical Engineering, Rutgers University, Piscataway, New Jersey, United States.

Biological cells can inspire the creation of nanoparticles equipped to store and release hydrophobic drug molecules upon demand. Lipid vesicles impregnated with alpha-helical peptides have demonstrated the clustering of the peptides under equilibrium. The formation of thick, amphiphilic, transmembrane channels via the self-organization of the peptides could be potentially used for the on-demand release of small drug molecules from the hydrophobic core of a vesicle bilayer. We are interested in understanding the driving forces responsible for cluster formations and evaluating their effects using the Molecular Dynamics simulation technique. Coarse grained representations of the molecules are used to resolve the extended spatiotemporal scales relevant to the problem at hand. The bonded and non-bonded interactions between the particles is captured by the Martini force field. We investigate the role of peptide concentration and helical separation on the cluster formation. We find the cluster size to be dependent more on helical separation as compared to peptide concentration. Additionally, we test the role of hydrophobic mismatch to understand the effect of electrostatic interactions between the peptides and lipid molecules. Our results demonstrate negative mismatch to result in larger cluster sizes as compared to a zero hydrophobic mismatch condition due to larger perturbations in the vesicle monolayers.

**8:15 AM BM09.01.02**
**Self-Assembly of Membrane-Active Peptides into Macromolecular-Size Pores** Kalina Hristova[1], Sijia Li[1], Sarah Kim[1], Anna Pittman[2], Gavin King[2] and William Wimley[3]; [1]Johns Hopkins University, Baltimore, Maryland, United States; [2]University of Missouri, Columbia, Missouri, United States; [3]Tulane University, New Orleans, Louisiana, United States.

Peptides that self-assemble into pore-like structures in lipid bilayers could have utility in a variety of biotechnological and clinical applications due to their ability to breach the barrier imposed by lipid bilayers. To empower such discoveries, we use rationally designed peptide libraries and high-throughput screens to select peptides based on a particular property, in this case macromolecular-size bilayer poration. Towards this goal, we designed a library based on the bee venom peptide melittin, and we developed a high throughput screen that reports on the passage of macromolecules across lipid bilayers. We identified two peptide families that efficiently assemble into large pore-like structures. One of the families is highly active at pH 7. The other peptide family is pH sensitive, as its self-assembly is triggered by low pH. The pH-triggered peptides could be used for endosomal release of uptaken polar molecules into the cell cytosol, upon endosomal acidification. They also could be used in cancer therapies to selectively permeabilize the plasma membranes of cancer cells, since the vicinity of solid tumors is often acidic. Additional generations can be screened to further fine-tune the properties of these peptides.

**8:30 AM BM09.01.03**
**Exploring the Tubability of the Aggregation and Gelation Process of the Tripeptide Glycyl-Alanyl-Glycine (GAG)** David DiGuiseppi[1], Lavenia Thursch[2], Nicolas Alvarez[2] and Reinhard Schweitzer-Stenner[1]; [1]Department of Chemistry, Drexel University, Philadelphia, Pennsylvania, United States; [2]Department of Chemical and Biological Engineering, Drexel University, Philadelphia, Pennsylvania, United States.

Self-assembly of biomolecules is a prominent issue explored in biomedical, biophysical, and bio-material research. Understanding how and why certain peptides/proteins prefer to self-assemble into larger networks can reveal the mechanism of amyloid formation and assist in bottom-up designs of supramolecular structures like gels and nanotubes. Some low molecular weight di- or tripeptides with aromatic residues and terminal groups have been shown to form gels. Contrary to expectations, we recently discovered that cationic glycylalanylglycine (GAG), a tripeptide of low hydrophobicity, forms a gel in 55 mol% ethanol/45 mol% water at room temperature if the concentration exceeds 200 mM. The underlying structure is comprised of unusually long crystalline fibrils (in the $10^{-5}$m range), which do not exhibit the canonical β-sheet structure. Rheological data and vibrational circular dichroism spectra suggest the existence of two different gel phases, one formed between 15° and 35°C with left handed twisted fibrils and G' values at ca. $2*10^4$ Pa and another one formed below 15°C with right handed twisted fibrils and G' values close to $10^5$ Pa. Results from DFT calculations indicate that the two phases might be underlied by rather differently structured fibrils. The fluorescence kinetics probing the incorporation of thioflavin T into the hydrophobic interior

of fibrils indicate a retarded diffusion of the fluorophore into fibrils that formed rather quickly after incubation above 15°C, while fluorescence increase, and gelation proceed on a similar time scale for the gel phase formed below this temperature. Upon increasing the temperature, it can preserve this capability until the melting temperature is reached, which suggests that this gel phase has all what it takes to function as a drug delivery system. The potential reformation process of the fibrils probed by UVCD, rheology, and microscopy show that after sitting for 16h above the melting temperature, the fibrils do not have the ability to grow back. Instead, microscopic images suggest the formation of a crystal-type structure that forms in its place. Our results therefore suggest that the gel phases are meta-stable states of the system that form more quickly at or below room temperature. We care currently working on optimizing the gelation/melting conditions for specific biotechnological applications of the gel as well as characterizing the observed crystal-type structure.

**8:45 AM BM09.01.04**
**Neutral Self-Assembling Multidomain Peptides—Steric Impediment Regulates Nanofiber Formation and Materials Properties** Tania L. Lopez Silva, David G. Leach, I-Che Li, Xinran Wang and Jeffrey Hartgerink; Chemistry Department, Rice University, Houston, Texas, United States.

Peptide-based materials have drawn high interest for their use in biomedical applications such as drug delivery, cell encapsulation, and tissue regeneration. Particularly, self-assembling peptide hydrogels have shown promising properties as biomaterials since their properties and functionality are tunable by their peptide sequence. For example, they are inherently biocompatible and biodegradable, their nanofibrous structure resembles the extracellular matrix, and they form materials with high-water content. Generally, these peptides utilize ionic amino acids to control self-assembly by changing the pH or ionic strength. Included in these group are the self-assembling Multidomain Peptide nanofibers (MDP), composed of an amphiphilic β-sheet forming core and flanking charged domains, which increase peptide solubility and make the peptide material responsive to pH changes and the presence of ions.

It is known that the biological response and cell behavior is highly dependent on the chemistry of the materials. Positive polymers promote cell adhesion and proliferation while showing concentration-dependent cytotoxicity, whereas neutral polymers, such as PEG, are frequently inert, biocompatible and non-immunogenic. Previously, all MDPs were either positively or negatively charged; therefore, expanding the scope of MDPs to neutral, non-ionic peptides will make distinct biological properties available that are not present in highly charged peptides.

Strategies to control the self-assembly of non-ionic peptides is limited because these peptides tend to have low solubility, aggregate or precipitate in aqueous solutions, making the formation of finite supramolecular structures and self-assembled hydrogels challenging. In this project, we present an alternative mechanism to control the self-assembly of neutral, uncharged multidomain peptides by utilizing steric impediment. Through the study of a series of neutral peptides, we analyzed the effect of the steric interactions on the peptide solubility, aggregation, nanostructure, and hydrogelation. From the series, a novel neutral multidomain peptide hydrogel was developed, which is inert to pH variation and ionic strength. This novel material showed promising properties for biomedical, cell preservation and tissue regeneration applications.

**9:00 AM *BM09.01.05**
**Self-Assembly of 2D Peptide-Based Crystalline Nanomaterials** Vincent P. Conticello; Emory University, Atlanta, Georgia, United States.

Structurally defined materials on the nanometer length-scale have been historically the most challenging to rationally construct and the most difficult to structurally analyze. Sequence-specific biomolecules, i.e., proteins and nucleic acids, have advantages as design elements for construction of these types of nano-scale materials in that correlations can be drawn between sequence and higher order structure, potentially affording ordered assemblies in which functional properties can be controlled through the progression of structural hierarchy encoded at the molecular level. The predictable design of self-assembled structures requires precise structural control of the interfaces between peptide subunits (protomers). However, control of quaternary structure has proven to be challenging to reliably predict, as conservative changes in sequence can result in significant changes in higher order, i.e., supramolecular, structure. We have employed simple self-assembling peptides as building blocks for the construction of two-dimensional nano-scale assemblies. In contrast to filamentous assemblies (e.g., fibrils, ribbons, and tubes), protein-based two-dimensional assemblies occur relatively infrequently in native biological systems. We have demonstrated that extended and structurally defined two-dimensional assemblies can be constructed through lateral association of chiral rod-like subunits such as the collagen triple helix. The resultant assemblies can exhibit sequence-dependent control of structure, including growth in the lateral and/or axial dimensions. Moreover, the sheet-like assemblies can be integrated with other self-assembled biological structural motifs, such as DNA origami nano-tiles, to afford self-organized hybrid assemblies. Despite the potential for these two-dimensional assemblies as structurally defined nano-scale scaffolds, it remains challenging to reliably predict and control the structure of the assemblies based on sequence-structure correlations at present.

**9:30 AM BREAK**

**10:00 AM *BM09.01.06**
**Bio-Inspired Materials Linking Covalent and Supramolecular Polymers** Samuel I. Stupp; Northwestern University, Evanston, Illinois, United States.

Supramolecular soft matter is a rapidly emerging field that encompasses the rational use of organic molecules to design function in materials. The most promising systems are “supramolecular polymers” since one-dimensional catenation of structural units is a critical feature to create mechanically robust macroscopic systems and directed transport of charge in aligned morphologies. Supramolecular polymers, in contrast to macromolecules in which structural units are linked through covalent bonds, supramolecular systems are designed using additive noncovalent bonds that are tunable over a very broad range of binding energies encoded in the molecular structure of the “mers”. Furthermore, a major gap in the design of synthetic soft matter is the rational integration of covalent and supramolecular polymers, a concept that is used to craft function in the structures of living organisms. This lecture will describe first entirely supramolecular systems based on peptides and nucleic acids in which dynamics of non-covalently bonded monomers can reversibly form superstructures linked to mechanical and biological functions. Within the domain of hybrid systems in which covalent macromolecules are integrated with supramolecular structures, the lecture will describe materials inspired by muscles that are capable of transducing thermal to mechanical energy, light to mechanical energy, and light to chemical energy in photocatalytic materials.

**10:30 AM BM09.01.07**
**Self-Assembly of Hierarchical Cellular Materials from Amphiphic Triblock Peptides** Erik D. Spoerke, Brad Jones, Jill Wheeler, Jeffrey Vervacke, Christina Ting and Mark Stevens; Sandia National Laboratories, Albuquerque, New Mexico, United States.

Macromolecular self-assembly in biological systems takes many forms and enables countless functions across multiple length scales. Often, the structure and function of these assembled structures are dictated by subtle changes in the composition of the molecular building blocks that make up these materials. For example, simple amino acid substitutions can impart significant changes in the structure and function of protein assemblies. Inspired by this theme, we explore here the self-assembly of an ABC triblock peptide-oligoethylene oxide amphiphile with hydrophilic A and C blocks and a hydrophobic B peptide block. By varying the amino acid side chain size and hydrophobicity within the B-block, we observe aqueous self-assembly into polymorphic cellular particles with hierarchical structure and porosity ranging from giant vesicles with foam-like membranes to porous tubular architectures. These structures

are characterized microscopically and spectroscopically to determine the relationships between the varied peptide compositions, tunable intermolecular interactions, and the observed morphologies. Additional evaluation of these materials as vehicles for molecular encapsulation and as templates for secondary mineral templating reveal potential new strategies to control hierarchical materials synthesis and assembly through bio-inspired molecular building block design.
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**10:45 AM BM09.01.08**
**Modular Peptide-Polymer Conjugates—A Platform Technology for Mucin Analogues** Daniel French, Luis Navarro and Stefan Zauscher; Duke Univ, Durham, North Carolina, United States.

Mucins – the glycoprotein building-blocks of mucus – play diverse and crucial roles in the body. These functions range from lubrication of articular joints and the eye, to the protection of stomach endothelium from the harsh environment of the lumen, to modulation of microflora populations in the digestive and respiratory systems. Despite this diversity, these functions are all attributed to slight modifications in a general structure shared by all mucins: a telechelic triblock polypeptide comprised of terminal association moieties and a heavily glycosylated core which forms a hydrated bottle brush center. *In vivo*, these versatile functions are achieved by altering glycosylation patterns, crosslinking density, and targeting affinity in a modular fashion.
Inspired by this adaptability, we have emulated this general architecture in a modular conjugate analogue mucin platform which engenders general structural features preserved among mucins which we, and others, have identified as key to their function. To recapitulate the mucin backbone, we genetically tether and co-express terminal binding modules with a lysine-rich, elastin-like polypeptide (ELP) central scaffold. Binding modules may include sequences designed to target surfaces of interest, to facilitate intramolecular associations, or to direct surface conformation of our construct. The regularly-spaced lysines in the ELP scaffold can be harnessed for grafting synthetic polymer bristles. Bristle chemistry may be chosen for a desired property (including non-fouling character and lubricity) independent of the binding and scaffold modules. Our platform is, to our knowledge, the first to adapt the modularity of the mucin architecture into a bio-synthetic platform technology.
To demonstrate the application of our platform to clinically-relevant problems, we have tailored our mCAMP to osteoarthritis and kidney stone disease, two conditions infamous for profound morbidity and high prevalence. In tailoring our analogue mucin to cartilage, we hope to rival the performance of lubricin, a natural mucin which provides lubrication and wear protection to articular joints. Moreover, we seek to harness the properties of natural mucins and apply them to systems not naturally protected by mucinous coatings. In doing so, we have adapted our platform to binding calcium oxalate kidney stones. Association modules are designed to direct assembly on mineral surfaces as well as inhibit further mineralization. Moreover, these modules are designed to form intramolecular associations, facilitating a robust surface coating. The inclusion of non-fouling synthetic polymer bristles provides a means by which to inhibit protein-mediated crystal aggregation. In this platform technology, we have begun to develop a means by which to replicate not only the *in vivo* function of mucins, but to harness that function to meet additional clinical needs.

**11:00 AM BM09.01.09**
**Design of Bioresponsive Nanogels Inspired by Peptide-Glycan Interactions** Andrew Simonson[1], Atip Lawanprasert[1], Tyler Goralski[2], Kenneth Keiler[2] and Scott Medina[1]; [1]Biomedical Engineering, The Pennsylvania State University, University Park, Pennsylvania, United States; [2]Biochemistry and Molecular Biology, The Pennsylvania State University, University Park, Pennsylvania, United States.

Early investigations from The Medina Group identified that binding of cationic membrane-active peptides with negatively charged cell-surface glycans was a critical initiating step to potentiate the peptide's lytic action. Inspired by this natural system, we have designed a family of biohybrid nanomaterials assembled via electrostatic association of cationic peptides and anionic carbohydrates. Screening a series of peptide-polysaccharide pairs under electrospray synthesis conditions identified that poly-L-lysine (PLL) and hyaluronic acid (HA) rapidly co-assemble to yield nano-scale gel-like particles, which we refer to as nanogels. Importantly, using peptide-carbohydrate co-assembly allowed for direct encapsulation of both small molecule drugs and protein cargo into the nanogel carrier under mild aqueous conditions conducive to sensitive biomolecules. Further, we found that modulating the ratio of PLL and HA utilized during particle assembly yielded nanogels with tunable swelling profiles and failure rates, thus allowing for controlled temporal release of loaded cargo. *In vitro* testing demonstrates that nanogels exhibit versatile and complimentary mechanisms of cargo delivery depending on the biologic context. In mammalian cells, nanogels can deliver membrane-impermeable protein cargo to the cytoplasm by rapid internalization via endocytosis, followed by endosomal escape. Likewise, chemotherapeutic-loaded nanogels were capable of enhancing the potency of loaded drug by up to an order of magnitude towards both chemo-sensitive and -resistant tumor cell lines. Remarkably, in the presence of bacterial pathogens, nanogels show a very different behavior. The carrier is able to recruit microbes and permeabilize their cell wall to sensitize pathogens to the action of loaded antibiotic. In a notable example, delivery of vancomycin from nanogels enhanced the drug's potency by >15-fold towards a gram-positive strain. Even more surprising was the ability of nanogels to sensitize gram-negative pathogens to the action of vancomycin, which are otherwise innately resistant to the drug due to the low permeability of their cell wall. This adaptable bioactivity, in combination with their low toxicity towards human endothelial cells and erythrocytes, demonstrate that nanogels represent a versatile and bio-responsive carrier capable of augmenting and enhancing the utility of a broad range of biomolecular cargoes.

**11:15 AM BM09.01.10**
**Template-Driven Peptide Assembly Yields Ultrasound Guided Phase-Changing Nanomaterials** Janna N. Sloand[1], Scott A. Zinck[2], Joel P. Schneider[3], Julianna C. Simon[2] and Scott H. Medina[1]; [1]Department of Biomedical Engineering, The Pennsylvania State University, University Park, Pennsylvania, United States; [2]Department of Acoustics, The Pennsylvania State University, University Park, Pennsylvania, United States; [3]Chemical Biology Laboratory, National Cancer Institute, National Institutes of Health, Frederick, Maryland, United States.

Phase-changing nanoparticles (PCNs) are a class of materials that undergo solid-liquid-gas transitions in response to various engineered stimuli, leading to their application in fields that include thermal energy storage, bioelectronics and precision medicine. In particular, liquid-shelled perfluorocarbon PCNs that can be vaporized upon exposure to ultrasound (US) are poised to open unprecedented opportunities in nanomedicine and molecular imaging. However, despite recent progress, challenges remain in controlling the material properties and acoustic activation of PCNs, as well as overcoming the poor loading efficiency and delivery of biologic cargo from the carrier. Here, we describe the design and synthesis of a new class of PCNs recently prepared via templated peptide assembly, which we refer to as 'nano-peptisomes'. Nano-peptisome architecture develops from the spontaneous orientation of *de novo* designed peptide amphiphiles around an US-sensitive fluorinated droplet as the template. Utilizing peptide-assembly allows for facile particle synthesis, direct incorporation of bioactive sequences displayed from the peptide corona, and the ability to easily encapsulate biologics during particle preparation using a mild solvent exchange procedure. We find that nano-peptisome size can be precisely controlled by simply modulating the starting peptide and fluorinated solvent concentrations during synthesis, leading to programmable acoustic properties of the final carrier. Further, biomolecular cargo, including peptides and proteins, can be encapsulated within the particle core and directly delivered to the cytoplasm of cells upon US-mediated rupture of the carrier. Bio-imaging studies demonstrate that nano-peptisomes can be tracked and guided using diagnostic B-mode US, while Doppler imaging allows for real-time monitoring of particle activation and rupture in tissue mimetic gels. These results establish nanopeptisomes as a novel

theranostic platform capable of image-guided delivery of bioactive macromolecules into cells with spatial and temporal precision.

**11:30 AM *BM09.01.11**
**Biomolecules for Non-Biological Things—Materials Construction Through Peptide Design and Solution Assembly** Darrin J. Pochan; University of Delaware, Newark, Delaware, United States.

Self-assembly of molecules is an attractive materials construction strategy due to its simplicity in application. By considering peptidic molecules in the bottom-up materials self-assembly design process, one can take advantage of inherently biomolecular attributes; intramolecular folding events, secondary structure, and electrostatic interactions; in addition to more traditional self-assembling molecular attributes such as amphiphilicty, to define hierarchical material structure and consequent properties. A new solution assembled system comprised of theoretically designed coiled coil bundle motifs will be introduced. The molecules and nanostructures are not natural sequences and provide opportunity for arbitrary nanostructure creation with peptides. With control of the display of all amino acid side chains (both natural and non-natural) throughout the peptide bundles, desired physical and covalent (through appropriate "click" chemistry) interactions have been designed to produce one and two-dimensional nanostructures. One-dimensional nanostructures span exotically rigid rod molecules that produce a wide variety of liquid crystal phases to semi-flexible chains, the flexibility of which are controlled by the interbundle linking chemistry. The two dimensional nanostructure is formed by physical interactions and are nanostructures not observed in nature. All of the assemblies are responsive to temperature since the individual bundle building blocks are physically stabilized coiled coil bundles that can be melted and reformed with temperature. Additional, novel nanostructures to be discussed include uniform nanotubes as well as the templated growth of metallic nanoparticle on and in peptide nanostructures. Included in the discussion will be molecule design, hierarchical assembly pathway design and control, click chemistry reactions, and the characterization of nanostructure as well as inherent material properties (e.g. extreme stiffness, responsiveness to temperature and pH, stability in aqueous and organic solvents).

SESSION BM09.02: Peptide-Based Nanomaterials
Session Chairs: Darrin Pochan and Shuguang Zhang
Monday Afternoon, November 26, 2018
Sheraton, 2nd Floor, Back Bay A

**1:30 PM *BM09.02.01**
**Guiding Principles for Peptide-Based, Life-Like Nanotechnology** Rein Ulijn; Advanced Science Research Center (ASRC) at the Graduate Center, Hunter College, Glasgow, New York, United States.

Life's diverse molecular functions are largely based on only a small number of highly conserved building blocks- the twenty canonical amino acids. These building blocks are chemically simple, but when they are organized in three-dimensional structures of tremendous complexity, new properties emerge, giving rise to the extraordinary machinery of life. So, if just twenty simple building blocks- when appropriately assembled – give rise to the complexity and functionality that can sustain life- then this is clearly a very versatile construction set. Our overall goal is conceptually simple: to figure out how to make nanoscale systems and materials from biology's building blocks, and to apply these materials to diverse problems, that require them to be interfaced, ideally seamlessly, with living systems, or the natural environment. Different from other research groups, we have an unbiased approach, that is not guided by copying biological systems, and we keep these systems as simple as possible, which lowers barriers to application. The talk will focus on our latest results in three areas: (i) directed discovery of peptide nanostructures with new functions, by searching the sequence space; (ii) application of peptide nanostructures as functional materials (including customizable melanin pigments). (iii) actively assembling systems, that continuously turn over chemical fuels, enabling dynamic changes in structure and function.

**2:00 PM BM09.02.02**
**Large-Scale Self-Sorting in Supramolecular Assemblies** Charlotte H. Chen[1], Liam Palmer[2, 3] and Samuel I. Stupp[1, 2, 3]; [1]Materials Science and Engineering, Northwestern University, Evanston, Illinois, United States; [2]Chemistry, Northwestern University, Evanston, Illinois, United States; [3]Simpson Querrey Institute for BioNanotechnology, Chicago, Illinois, United States.

Hierarchical organization across length scales is ubiquitous in the superstructures of living organisms. These highly functional structures form through self-assembly, and have therefore inspired significant research activity on synthetic supramolecular materials over the past decade. We report here on a synthetic system containing two supramolecular nanoscale polymers, of very similar structure, that interestingly exhibit micron scale self-sorting. The two different supramolecular polymers are formed by peptide amphiphiles and each is labeled with a different small fluorescent dye, and based on earlier work were expected to undergo molecular exchange. We hypothesize that electrostatic charges on the nanofibers promote the self-organization of the fibers into micron scale hierarchical structures, which take the form of 2D crystals, in order to minimize charge repulsion. The propensity to self-sort is diminished when ions are present to screen the electrostatic charges thus disrupting the hierarchical structures. Our results provide insight on strategies to promote self-sorting superstructures versus co-assembly in supramolecular systems.

**2:15 PM BM09.02.03**
**Thermally Reversible Transmembrane Molecular Channels Formed by Self-Assembled Metal-Organic Complexes** Niveen Khashab; King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

Biological channels are molecular gatekeepers that control cellular traffic across cell membrane. Realizing the functional principle of these systems through artificial transmembrane pores with molecularly defined structures is instrumental for future bionanotechnology applications. In this work, thermoresponsive synthetic channels based on supramolecular metal-organic complexes (MOCs) have been constructed to transport cell impermeable cargo across the membrane. The channels can be reversibly controlled as they collapse when the temperature is increased and are simultaneously regenerated when the system is cooled down to room temperature. These ON/OFF molecular valves could be used to overcome multidrug resistance (MDR) in cancer cells and as building blocks for artificial cells.

**2:30 PM BM09.02.04**
**Incorporating Hierarchical Structure within Hydrogel Biomaterials Using Multifunctional Collagen Mimetic Peptides Toward Directing Stem Cell Fate** Eden Ford[1], Amber Hilderbrand[1], Chen Guo[1] and April Kloxin[1, 2]; [1]Chemical & Biomolecular Engineering, University of Delaware, Newark, Delaware, United States; [2]Material Science & Engineering, University of Delaware, Newark, Delaware, United States.

Extracellular matrix (ECM) properties are important regulators of cell function, particularly at early timepoints during bone healing. For example, physical and chemical properties of the ECM regulate cytoskeletal organization, proliferation, and migration of stem cells to the site of bone injuries for commencing repair. Controlling the presentation of such extracellular cues with molecularly engineered materials provides opportunities to direct bone regeneration. We hypothesize that engineering synthetic hydrogels to recapitulate aspects of the early stages of healing in healthy bone will promote stem cell invasion and remodeling processes toward improving bone regeneration of traumatic fractures or critical-sized defects. To test this, we have created well-defined materials to mimic the mechanical properties, biochemical content, and multiscale structure of native tissues, particularly the collagen-rich environment of the clot-like hematoma formed early in the wound healing process.

We have designed multifunctional collagen mimetic peptides (mfCMPs) that are variants of the Proline-Hydroxyproline-Glycine repeat unit of native collagen. Two variants of this peptide were synthesized: one promoting fibrillar assembly through ionic interactions using charged groups (CMP1a) and the other using hydrophobic interactions of aromatic groups on the C- and N-termini to promote end-to-end assembly (CMP2a). Circular dichroism was used to examine triple helical assembly of the peptides and measure associated melting temperatures, where melting temperatures of CMP1a and CMP2a were determined to be 45.0°C and 60.2°C, respectively. Further peptide assembly and fibril formation was investigated with transmission electron microscopy, where fibrils were observed that mimicked aspects of the hierarchical nanostructure of native collagen. For CMP1a, fibrils approximately 35 nm in width and on the order of 1 μm in length were observed, whereas for CMP2a, fibrils approximately 60 nm in width and on the order of 100 nm in length were observed. Toward studying cell response *in vitro*, these mfCMPs were covalently crosslinked within cell-degradable poly(ethylene glycol) hydrogels, and rheometry was used to characterize the resulting mechanical properties. Hydrogels with storage moduli in the range of 3500-4500 Pa were generated; further, good cell viability was observed within these unique matrices, with approximately 80% viable cells across conditions.

These studies support our hypothesis that incorporation of mfCMPs within a covalent hydrogel network captures aspects of the fibrillar structure of collagen on both the nano- and microscale toward providing a biomimetic matrix that recapitulates key cues found in 'soft' collagenous tissues. Ongoing studies of human mesenchymal stem cells within these materials support their relevance for multidimensional cell culture and suggest that the presence of mfCMPs influences cell-matrix interactions and observed cell response.

**2:45 PM BM09.02.05**
**Tuning Bioinspired Macromolecular Assembly with Cation-π Interactions** Matthew A. Gebbie[1], Jacob N. Israelachvili[2] and J. Herbert Waite[2]; [1]Stanford University, Stanford, California, United States; [2]University of California, Santa Barbara, Santa Barbara, California, United States.

Cation-π interactions govern the assembly of many bio-macromolecules, including the adhesion proteins of marine organisms. Increasingly, cation-π interactions are also implicated in pathological processes, like the formation of neurodegenerative protein aggregates. Thus, developing molecular level approaches for engineering cation-π interactions is of both fundamental and technological importance. Although cation-π bonding has been extensively studied for gas phase ion-aromatic pairs, the energetics of cation-π adhesion in biological and biomineral interfaces, where many binding pairs are in close proximity, remains uncharted. In this seminar, I will discuss using molecular force spectroscopy, supplemented by solid-state NMR measurements, to show that the adhesive properties of simple aromatic- and lysine-rich peptides rival those of the adhesion proteins of the marine mussel. Surprisingly, we find that peptides with the aromatic amino acid phenylalanine, a functional group that is conspicuously rare in mussel proteins, exhibit adhesion that significantly exceeds that of analogous mussel-mimetic peptides. More broadly, we find that interfacial confinement fundamentally alters the energetics of cation-π mediated assembly, an insight that is relevant for diverse areas, from influencing bio-controlled crystal formation to engineering novel bioinspired medical adhesives.

**3:00 PM BREAK**

**3:30 PM *BM09.02.06**
**Nanomaterials for Nervous Regeneration** Fabrizio Gelain; ISBREMIT, IRCCS Casa Sollievo della Sofferenza, San Giovanni Rotondo, Italy.

Peptidic biomaterials have been receiving great interest because of their easiness of scale-up production, absence of pathogen-transfer risk, biomimetic properties, nanostructured morphology and customization potential for the specific tissue engineering application. However, their proper usage requires the understanding of the multiple-phenomena taking place at different scale levels during self-assembling. In this presentation, focused on the nanotech advancements in the field of nervous regeneration, we will see some multi-disciplinary researches and advances toward the regeneration of spinal cord injuries. This will bring us from coarse-grained molecular dynamics to electro-spinning of self-assembling peptides (SAPs), from cross-linking of SAPs to 3D high-denisty neural stem cells cultures. Lastly, in vivo tests of SAP prosthese in animal models of sub-acute and cronic SCI will be discussed.

**4:00 PM BM09.02.07**
**Learning from Nature to Form New Organic Materials for Tissue Regeneration** Lihi Abramovich; Oral Biology, Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel.

Molecular self-assembly is a key direction in current nanotechnology based material science fields. In this approach, the physical properties of the formed assemblies are directed by the inherent characteristics of the specific building blocks used. Molecular co-assembly at varied stoichiometry substantially increases the structural and functional diversity of the formed assemblies, thus allowing tuning of both their architecture as well as their physical properties. In particular, building blocks of short peptides and amino acids can form ordered assemblies such as nanotubes, nanospheres and 3D-hydrogels. These assemblies were shown to have unique mechanical, optical, piezoelectric and semiconductive properties. Yet, the control over the physical properties of the structure has remained challenging. For example, controlling nanotube length in solution is difficult, due to the inherent sequential self-assembly mechanism. Another example is the control of 3D-hydrogel scaffold's physical properties, including mechanical strength, degradation profile and injectability, which are important for tissue engineering applications.
Here, in line with polymer chemistry paradigms, we applied a supramolecular polymer co-assembly methodology to modulate the physical properties of peptide nanotubes and hydrogel scaffolds. Utilizing this approach with peptide nanotubes, we achieved narrow nanotube length distribution by adjusting the molecular ratio between the two building blocks; the diphenylalanine assembly unit and its end-capped analogue. In addition, applying a co-assembly approach on hydrogel forming peptides resulted in a synergistic modulation of the mechanical properties, forming extraordinary rigid hydrogels. Furthermore, we designed organic-inorganic scaffold for bone tissue regeneration.
This work provides a conceptual framework for the utilization of co-assembly strategies to push the limits of nanostructures physical properties obtained through self-assembly.

**References**

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**4:15 PM BM09.02.08**
**An Investigation on the Assembly of Particles in a Structurally Colored Protease-Responsive Particle Hydrogel—The Role of Particle Size and Charge** Leopoldo Torres[1], John L. Daristotle[1], Omar B. Ayyub[4], Bianca Meinhardt[4], Havisha Garimella[1], Soenke Seifert[2], Nicholas Bedford[3], Taylor J. Woehl[4] and Peter Kofinas[4]; [1]Fischell Department of Bioengineering, University of Maryland College Park, College Park, Maryland, United States; [2]Advance Photon Source, Argonne National Laboratory, Argonne, Illinois, United States; [3]Chemical Engineering, University of New South Wales, Kensington, New South Wales, Australia; [4]Chemical and Biomolecular Engineering, University of Maryland College Park, College Park , Maryland, United States.

Pathogens can thrive in an abundance of environments, and pose a significant threat to human health when irrigation or drinking sources become contaminated. The ability to detect the presence of pathogens or biomarkers, such as proteases, using a biosensing platform that is passive and requires no power can help monitor and prevent outbreaks of infectious diseases. We have developed a tunable protease-responsive platform that demonstrated a red-to-blue color shift for all target molecule concentrations between 20 nM and 4000 nM. Structurally colored particle hydrogels were fabricated by centrifuging monodisperse silica particles along with a 4-arm polyethylene glycol (PEG) and a protease-specific peptide linker into a close-packed microstructure, followed by UV irradiation to polymerize the composite. These films swelled in aqueous solutions, and color shift towards the red region of reflected visible light in response to the degree of swelling. Upon degradation of the peptide crosslink, the particles reassembled into a close-packed structure with interparticle spacing less than the initially centrifuged material. This reduction in particle spacing produced a 240 nm color change from the swollen state to the reassembled state of the material for 205 nm particle composites.

To elucidate the mechanism responsible for the color change, we investigated the role of particle size and charge, and polymer concentration in reassembly after degradation. Both particle size and surface functionalization were varied to produce composites with a range of observable structural colors. The reassembled materials reflected shorter wavelengths than their initially fabricated counterparts, indicating that the interparticle spacing had decreased as much as 45 nm for hydrogels with 230 nm particles. In addition, the reassembled composites reflected nearly identical wavelengths independent of the starting polymer weight fraction in the hydrogel. Ultra-small angle x-ray scattering confirmed that the interparticle spacing decreased and the spacing was the same for the reassembled composites. While the particle size or polymer content did not inhibit the reassembly process, particle surface charge was crucial to the reassembly mechanism. Only highly negative (-60mV) particles reassembled to produce structurally colored composites. PEGylated particle hydrogels did not reassemble, and the corresponding composites degraded into the protease solution. Composites with positively charged (+30mV) particle surfaces aggregated irreversibly into a material that appeared white due to incoherent scattering of visible light. Interaction potential models demonstrated that depletion forces provide necessary attraction for reassembly, with a range of up to 120 nm. These findings offer insight into the parameters that will enable passive monitoring of proteases with precise control of structurally colored particle hydrogel responses.

**4:30 PM BM09.02.09**
**Anti-Biofilm Activity of Graphene Quantum Dots via Self-Assembly with Bacterial Amyloid Proteins** Yichun Wang, Usha Kadiyala, Zhi-bei Qu, Paolo Elvati, Angela Violi, Scott VanEpps and Nicholas A. Kotov; Chemical Engineering, University of Michigan, Ann Arbor, Michigan, United States.

Bacterial communities, known as biofilms, cause multiple technological and health problems and represent an essential part of Earth's ecosystem. The environmental resilience and sophisticated organization and of biofilms acting as a multicellular organism is enabled by extracellular matrix (ECM) that creates a protective network of biomolecules around the bacterial communities. The current antibiofilm agents can interfere with ECM production but, being based on small molecules, they can be degraded by bacteria and diffuse away from biofilms, which reduce their efficacy. Here we show that graphene quantum dots (GQDs) can effectively suppress the growth of *Staphylococcus aureus* biofilms by preventing the self-assembly of amyloid fibers - the essential component of ECM. Mimicking peptide-binding biomolecules, GQDs form supramolecular complexes with phenol soluble modulins (PSMs), the peptide monomers of amyloid fibers. Experimental and computational results show that GQDs dock at the *N*-terminal of the peptide and change the secondary structure of PSM, which disrupts their fibrillation. Concomitantly, the resulting free PSM monomers turn on biofilm dispersion signaling pathways that enhance the inhibitory effect. The two-prong anti-biofilm activity of GQDs offer a new strategy for manipulation of ECMs of bacterial communities.

**4:45 PM BM09.02.10**
**Soft to Hard Biomimetic Constructs Using Recombinant Proteins Undergoing Conformational Transition** Hortense Le Ferrand, Bartosz Gabryelczyk, Cai Hao and Ali Miserez; Nanyang Technological University, Singapore, Singapore.

Synthetic mechanical gradients based on synthetic and biocompatible hydrogels currently do not achieve the steep soft to hard transition found in many biological materials like squid beaks or osteochondral cartilage [1]. Indeed, it is difficult to obtain tight molecular packing and high crosslinking density using conventional polymeric building blocks. Here, we employ the recombinantly expressed protein HBP-1 found in the beak of squids, and make use of its folding in presence of polyelectrolytes to expel water and attain high packing density [2,3]. Under acidic pH and in the presence of chitosan, HBP-1 undergoes a conformational transition from predominantly random coil into ß-sheet-rich. At increased ionic strength, this conformation change leads to a phase separation from soluble to liquid droplets and a hydrogel-like phase. At a constant volume fraction of chitosan, the elastic modulus of the HBP-1/chitosan composite increases with the protein content. After drying and cross-linking using catechol chemistry, the resulting organic material shows similar trend under fully hydrated conditions. This observation is reminiscent to what is observed in the native squid beak. Furthermore, concentration gradients can be modeled based on molecular diffusion and phase separation. With this knowledge, gradients of controlled steepness can be obtained. The crosslinked gradient results in an increase of elastic modulus from 0.08 up to 1 GPa despite containing 60 vol% of water. The approach explored here may open new avenues for the fabrication of graded materials based solely on organic biomaterials with potential applications for orthopaedic devices and soft-to-hard attachment in hydrated environments.

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[2] Y. Tan, S. Hoon, P.A. Guerette, W.Wei, A. Ghadban, C. Hao, A. Miserez, J.H. Waite, Infiltration of chitin by protein coacervates defines the squid beak mechanical gradient, *Nature Chemical Biology*, **11**, 488 (2015).

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SESSION BM09.03: Protein-Based Materials
Session Chairs: Fabrizio Gelain and Shuguang Zhang
Tuesday Morning, November 27, 2018
Sheraton, 2nd Floor, Back Bay A

**8:00 AM *BM09.03.01**
**CryoTEM Reveals the Molecular Mechanism of Polymorph Selection in Protein Crystallization** Mike Sleutel[1], Alexander E. Van Driessche[2] and Nico Sommerdijk[3]; [1]Vrije Universiteit Brussel, Elsene, Belgium; [2] Univ. Grenoble Alpes, CNRS, ISTerre, Grenoble, France; [3] Institute for Complex Molecular Systems, Eindhoven University of Technology, Eindhoven, Netherlands.

Macromolecular condensed phases such as protein crystals and gels bear great medical, scientific and industrial relevance, yet a molecular understanding of their initial stages of formation is still missing. Insights on the mechanism of nucleation have the potential to resolve one of the longest-standing questions of crystallization, i.e. polymorph selection. To gain control over the emerging polymorph one needs to have a molecular-level understanding of the pathways leading to the various macroscopic states and the underlying selection mechanisms that govern the process. Here we address the issue by capturing protein crystals at birth using time-resolved cryo-transmission electron microscopy and uncover at molecular resolution the nucleation pathways of the protein glucose isomerase into two crystalline and one gelled state. We show that polymorph selection takes place at the earliest stages of transformation and is based on the specific building blocks (monomers and nanorods) for each space group. Moreover, we demonstrate control over the system by selectively forming desired polymorphs through tuning of the directionality and specificity of inter-molecular bonding. These new insights on the mechanisms of nucleation and polymorph selection open new avenues towards the control of macromolecular phase transitions, which is crucial in the further development of protein-based drug delivery systems and macromolecular crystallography.

**8:30 AM BM09.03.02**
**Building Hierarchically-Ordered 3D Nanomaterials Using 2D Self-Assembling Protein Arrays** Francesca Manea and Caroline Ajo-Franklin; Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Leveraging self-assembly to pattern proteinaceous crystalline arrays in 2D and 3D offers a highly scalable, bottom up approach to develop nanomaterials with new catalytic, optical electronic or structural applications. However, introducing multiple sites of embellishment into existing 2D protein arrays currently utilizes weak interactions that are either sensitive to external conditions or challenging to re-engineer, limiting the ability to program in bifunctionality and new 3D configurations. Here we address these challenges by developing a means to introduce two orthogonal covalent linkages at multiple sites in a highly robust, thermostable 2D crystalline-forming protein. We first engineered the surface-layer (S-layer) protein SbsB from Geobacillus stearothermophilus to display SpyTag or SnoopTag at the C-terminal and two newly-identified locations within SbsB monomer. These regions were able to accommodate SpyTag or SnoopTag peptide tags without affecting the 2D lattice structure. The introduction of tags at distinct locations enabled orthogonal and covalent binding with high precision of SpyCatcher- or SnoopCatcher-protein fusions to micron-sized 2D sheets. By introducing different types of bifunctional crosslinkers, the dual functionalized nanosheets could be programmed to self-assemble into different 3D lamellae, all of which retain their nanoscale order. Additionally, these nanosheets can be functionalized to display two distinct nanomaterial, yielding nanomaterials with emergent optoelectronic properties. Thus, our work creates a modular protein platform that can be facilely programmed to create dual-functionalized 2D and lamellar 3D nanomaterials with novel catalytic, optoelectronic and mechanical properties.

**8:45 AM BM09.03.03**
**Intracellular Phase-Separated Assemblies of Engineered Disordered Proteins** Ming-Tzo Wei and Cliff Brangwynne; Princeton University, Princeton, New Jersey, United States.

There is currently a growing interest in biopolymer phase transitions, particularly those involving intrinsically disordered proteins/regions (IDPs/IDRs). It has been found that intracellular liquid-liquid phase separations underlie the assembly of many non-membranous organelles such as P granules, nucleoli, and stress granules. However, little is known about the physics of these organelles, including their internal molecular organization and feedback between their molecular and mesoscale properties. Progress on these questions has been hampered by the lack of detailed phase diagrams, which would elucidate how molecular interactions give rise to emergent droplet properties, particularly condensed-protein concentrations and their physical characteristics.

To answer these questions, we investigate the inter-molecular interaction strengths and the full binodal of a phase-separating disordered protein that induces in-vivo phase transitions, utilizing a novel technique, ultrafast-scanning fluorescence correlation spectroscopy. These measurements led to the recent discovery that phase-separated protein droplets have unusually low densities with large void volumes. The data demonstrate how sequence-encoded conformational fluctuations of IDRs give rise to low overlap volume fractions for driving phase separations. Using inter-molecular interactions of native non-membranous organelles, we develop an optogenetic platform that permits light activation of IDR-mediated phase transitions in living cells. Inter-molecular interaction strengths are quantified and demonstrated how IDR sequences determine intracellular phase separation. These studies can elucidate not only physiological phase transitions but also their links to pathological aggregates.

Our results provide a holistic picture of the dynamics and internal organization of phase separated organelles. By uncovering the relationship between molecular level interactions and emergent mesoscale material properties, this work is foundational for understanding the form, function and potential dysfunction of intracellular phase separated assemblies. Our study has significant impact for an extensive community of researchers, with interests spanning biomaterials, bio-inspired materials, macromolecular assembly, self-assembly, intracellular phase separation, disordered proteins dynamics, polymer chemistry, and bioengineering applications of synthesized intracellular biomimetic materials.

**9:00 AM BM09.03.04**
**Altered Energy-Landscape and Self-Assembly of Protein Crystalline 2D Array at Solid-Liquid Interface** Shuai Zhang[1], Robert Alberstein[2], F. Akif Tezcan[2] and James J. De Yoreo[1]; [1]Pacific Northwest National Laboratory, Richland, Washington, United States; [2]Department of Chemistry and Biochemistry, University of California, San Diego, San Diego, California, United States.

Protein 2D materials possess diverse sophisticated and synergistic structures, and inherent chemical and biological functions. Harnessing this paradigm of protein 2D materials for bottom-up biomaterial design, synthesis and application is an attractive task with promising perspectives in biomimetic and material science. Inspired by nature cases, various strategies have been developed to construct protein 2D crystals in bulk solution. Recently, computational protein design methodology has considerably improved the structural and functional complexities of protein 2D/3D supramolecular structures from scratch.[1, 2] Besides growth in solution, solid-liquid interface has also been used to template few-layer protein 2D materials. However, the solid-liquid interface that is used to artificially grow protein 2D supramolecular structures is generally limited to supported liquid bilayer. It is still not quite clear how solvent mediated protein-surface interactions to define protein thermodynamics, structure and function at solid-liquid interface. That is the obstacle for artificial design and functional applications of protein 2D crystalline arrays in future.
To address those issues, we assembled the variant of L-rhamnulose-1-phosphate aldolase (RhuA), $^{C98}$RhuA[3], with incorporated Cys mutants, into crystalline 2D arrays on solid-liquid interface of mica. By carefully selecting cations and controlling their concentration, we create isotropic protein mono-/bi-layer 2D crystals with controlled packing patterns. It is surprising that the crystallizations of the first and second layers is bimodal that follows non-classical and classical pathways, respectively. We also proved that solvent mediated protein-surface interactions can alternate the energy-landscape of protein self-assembly from that in bulk to stabilize the original intermediate and quasi stable phase. $^{C98}$RhuA can epitaxially grow on top of the surface that has different symmetry. All the findings inspire the novel strategy to synthesize protein crystalline 2D arrays at solid-liquid interface artificially. They also help to elucidate the growth modal of protein 2D architectures at solid-liquid interface. They remind us the importance of solvent mediated surface templating in the self-assembly of protein 2D structures both in nature and in human manner.

1. Huang, P.-S., S.E. Boyken, and D. Baker, *The coming of age of de novo protein design.* Nature, 2016. **537**: p. 320.
2. Gonen, S., et al., *Design of ordered two-dimensional arrays mediated by noncovalent protein-protein interfaces.* Science, 2015. **348**(6241): p. 1365.
3. Suzuki, Y., et al., *Self-assembly of coherently dynamic, auxetic, two-dimensional protein crystals.* Nature, 2016. **533**(7603): p. 369-373.

**9:15 AM BM09.03.05**
**Microbial Factories for Programmed Production of Functional Biomaterials** Avinash Manjula Basavanna[1, 2], Anna Duraj-Thatte[1, 2] and Neel Joshi[1, 2]; [1]Wyss Institute for Biologically Inspired Engineering, Boston, Massachusetts, United States; [2]Harvard University, Boston, Massachusetts, United States.

Biological systems are highly complex and sophisticated with unparalleled structure-function correlations. Remarkably, biological systems produce materials with extraordinary properties and functions under ambient conditions, which is in total contrast to humans' heat-beat-treat strategies. Thus, the capabilities of a technology by which biological networks of a cell can be programmed, offers tremendous potential as cellular factories and to produce biomaterials for various functional applications.

In this regard, we employ a novel technology entitled Biofilm-Integrated Nanofiber Display (BIND) that focuses on the curli system-the primary proteinaceous structural component of *E. coli* biofilms. Curli are highly robust functional amyloid nanofibers (diameter 4-7 nm) formed by the extracellular self-assembly of a small (13 kDa) secreted protein, CsgA. By genetic engineering, artificial peptide domains were grafted to the amyloid protein CsgA and the resulting CsgA fusion proteins were successfully secreted from the *E. coli* cells. Remarkably, these engineered fusion proteins were found to extracellularly self-assemble into amyloid nanofiber networks and also exhibited the characteristic functions of the grafted artificial peptide domains. By using BIND technology, *E. coli* biofilm matrix is conferred with several artificial functions for nanomedicinal, nanomechanical and nanoelectronics applications.

**9:30 AM BREAK**

**10:00 AM *BM09.03.06**
**S-Layers—Principles and Applications** Uwe Sleytr and Dietmar Pum; Nanobiotechnology, Univ Bodenkultur, Vienna, Austria.

One of the key challenges in nanobiotechnology is the utilization of self-assembly systems wherein molecules spontaneously associate into reproducible aggregates and supromolecular structures. In this contribution, the basic principles of crystalline bacterial surface layers (S-layers) and their use as patterning elements will be described. The broad application potential of S-layers in nanobiotechnology is based on the specific intrinsic features of these monomolecular arrays which are composed of identical protein or glycoprotein subunits. Most important, physicochemical properties and functional groups on the protein lattice are arranged in well-defined positions. Many applications of S-layers depend on the capability of the isolated subunits to recrystallize into monomolecular arrays in suspension or on suitable surfaces (e.g. polymers, metals, silicon wafers) or interfaces (e.g. lipid films, liposomes, emulsomes). S-layers also represent a unique structural basis and patterning element for generating more complex supramolecular structures involving all major classes of biological molecules Thus, S-layers fulfil key requirements as building blocks for the production of new supramolecular materials and nanoscale devices as required in nanobiotechnology and synthetic biology.

Sleytr, U.B., Schuster, B., Egelseer, E.M., Pum, D. (2014) FEMS Microbiol Rev, 38, 823-864.
Pum, D., Toca-Herrera, J.L., Sleytr, U.B. (2014) Nanotechnology, 25, 312001.
Sleytr, U.B. 2016. Curiosity and Passion for Science and Art. World Scientific. ISBN 9813141816

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**10:30 AM BM09.03.07**
**Controlled Formation of Enzyme-Scaffold Complex for Biocatalysis Using a Self-Assembling Protein Template** Samuel Lim[1], Florence Barraud[1], Sophia Prem[1], Dominic J. Glover[2] and Douglas S. Clark[1]; [1]Department of Chemical and Biomolecular Engineering, University of California, Berkeley, Berkeley, California, United States; [2]School of Biotechnology and Biomolecular Sciences, University of New South Wales, Sydney, New South Wales, Australia.

In nature, enzymes that catalyze multi-step reactions are often organized in close proximity to allow the efficient channeling of intermediates from one active site to another. Diverse synthetic scaffolds based on DNA and proteins have been designed to mimic such spatial control of enzymes, and have proven successful in facilitating cascade reactions. Recent studies revealed that such enhanced catalysis can also result from formation of enzyme agglomerates rather than direct channeling of intermediates between adjacent enzymes, highlighting the need to engineer the interactions that define metabolic clusters. Thus, there is a demand for scaffolds that can effectively crosslink with each other to form higher-order structures in a programmable manner, in addition to simply templating the enzymes.

The g-prefoldin (gPFD) is a filamentous protein isolated from the hyperthermophilic archaeon *Methanocaldococcus jannaschii*; its remarkable stability,

unique modularity, and self-assembly into filaments with chaperone activity render it an ideal building block for the bottom-up construction of functionalized protein nanostructures. Here we propose a strategy to utilize the gPFD to build enzyme agglomerates in tunable fashion. Using the combinations of orthogonal protein-peptide bioconjugation pairs, the gPFD filaments displaying the peptide tags are first conjugated with the enzymes, and then crosslinked using the linker proteins. Thus, the extent of crosslinking is tunable through simply varying the stoichiometry between the scaffold and linker proteins.

We verified the gPFD scaffold's ability to cluster enzymes in proximity using FRET analysis of the filaments containing fluorescent protein pairs. Subsequently, we investigated the effect of agglomerate formation on the catalytic activities of multi-step reactions using two different model system pairings: glucose oxidase (GOX)-horseradish peroxidase (HRP) and alcohol dehydrogenase (ADH)-aldehyde dehydrogenase (ALDH). Ultimately, the ability to fabricate enzyme-scaffold complexes with programmable stoichiometry and dimensions will enable better control over single- and multi-step enzymatic catalysis.

**10:45 AM BM09.03.08**
**Developing Controllable Polymer-Enzyme Core-Shell Structures through Hierarchical Assembly** Tao Li[1, 2]; [1]Argonne National Laboratory, Downers Grove, Illinois, United States; [2]Chemistry and Biochemistry, Northern Illinois University, DeKalb, Illinois, United States.

The development of new structures that can stabilize, organize, and control the activity and stability of enzymes has been well investigated, but with limited success. The major challenge is that modified enzyme activity and stability are not comparable to that of the free enzyme, and enzyme recovery can be difficult. Recently, we developed a method that allows enzyme conformation and functionality to be preserved by assembling the polymers and enzyme into a hierarchical structure. In addition, *in situ* X-ray scattering has been used to study the co-assembly process of poly(4-vinylpyridine) (P4VP) and enzyme. Once enzyme and polymer were mixed, the assembly occurred immediately, and the protein remains their spherical shape on the surface of P4VP. Meanwhile, several beta-glucosidases were purified on a scale of several hundred mg and their activities and thermal stabilities were tested. Furthermore, one of the beta-glucosidases has been demonstrated to be assembled with P4VP to form polymer/protein core/shell structures, which are well characterized using DLS, SAXS and TEM.
We also found that solvents affect the activity of the enzyme. Five different water-soluble solvents have been tested, such as THF, DMF, DMSO, methanol and ethanol. An interesting result is that the enzyme retained its activity even at methanol concentration of up to 30% while losing the activity for the other four solvents at the same solvent concentration.

**11:00 AM BM09.03.09**
**Mimicking Dividing Cells by Assembly of Protein Structures Inside Aqueous Two-Phase Droplets** Anderson Shum[1], Yang Song[1], Tuomas Knowles[2] and Thomas Michaels[2]; [1]University of Hong Kong, Hong Kong, Hong Kong; [2]Chemistry, University of Cambridge, Cambridge, United Kingdom.

In this work, we demonstrate that assembly of macromolecules, such as proteins, can cause aqueous droplets to exhibit division, even in the absence of a cell membrane. The all-aqueous nature of the systems results in tunable interfacial tension, affinity partitioning and osmotic responses. The solubility of different types of macromolecules across the interfaces enables new strategies to assemble structures at the droplet interfaces. While the significantly lower interfacial tension can make stabilization of the interface difficult due to the slow adsorption dynamics by surfactants and particles, structures that have been assembled at the interfaces can be easily expelled. This contributes to the more sophisticated dynamics of the hierarhically structured all-aqueous droplets. These droplets have great potential to be utilized as templates for fabricating materials with novel properties.

**11:15 AM BM09.03.10**
**Self-Assembly of Elastin-b-Collagen-Like Conjugates Mediated by Triple Helical Parameters** Lucas Dunshee[1], Kristi L. Kiick[2] and Millicent Sullivan[1]; [1]Chemical and Biomolecular Engineering, University of Delaware, Newark, Delaware, United States; [2]Materials Science and Engineering, University of Delaware, Newark, Delaware, United States.

Physiochemical irregularities within extracellular matrix (ECM) proteins such as collagen can lead to a wide range of connective tissue disorders including osteogenesis imperfecta and osteoarthritis. Current pharmaceutical regimens to treat such diseases suffer from off-target effects, suggesting that new approaches for targeted delivery are necessary. In the last decade, ECM-inspired polypeptide materials have garnered significant interest for their ability to selectively mimic specific matrix components such as collagens and elastins, offering new opportunities to control drug delivery within specific tissues. For example, triple helix forming collagen-like peptides (CLPs) comprising $(Gly\text{-}Pro\text{-}Hyp)_n$ amino acid repeats can hybridize with high efficiency to denatured collagen proteins in the body via thermal annealing of peptide and protein single strands into a stable triple helix. Additionally, elastin-like peptides (ELPs) that consist of $(Val\text{-}Pro\text{-}Gly\text{-}X_{AA}\text{-}Gly)_n$ (where $X_{AA}$ is any amino acid with the exception of proline) amino acid repeats possess a lower critical solution temperature in which aggregation occurs upon heating above this temperature, making ELPs ideal candidates for on demand drug delivery behavior. Recently, our group has reported on the design of hybrid peptides with linked CLPs and ELPs, and the assembly of thermoresponsive, elastin-b-collagen-like peptide nanovesicles that are capable of dissociating at high temperature (70°C). These nanovesicles offer intriguing potential in drug delivery applications due to their dual thermoresponsivity and inherent ability to bind to degraded collagen protein. However, in order to make an ELP-CLP nanoparticle with optimal drug delivery properties such as physiologically relevant hybridization to degraded collagen protein, the critical parameters of their self-assembly must first be understood, specifically with respect to the CLP domain. To test the effects of the triple helical (CLP) melting temperature on temperature-dependent nanovesicle assembly and dissociation behavior a small library of ELP-CLP conjugates was made with varying numbers of CLP (G-X-Y) repeats and varied CLP sequences. These conjugates were characterized for their thermoresponsivity and their ability to form self-assembled structures. The melting temperature, repeat length, and overall hydrophilicity of the CLP domain were found to be of critical importance to nanoparticle formation.

**11:30 AM *BM09.03.11**
**Soft Functionalization of Silk Fibroin Materials and Bio-Flexible Devices** Xiang Yang Liu[1, 2]; [1]Department of Physics, FOS, National University of Singapore, Singapore, Singapore; [2]College of Physical Science and Technology, Xiamen University, Singapore, Singapore.

As an excellent flexible biomaterial, *Bombyx mori* silk fibroin materials offer exquisite mechanical, optical, and electrical properties which are advantageous toward the development of next-generation biocompatible electronic devices. In this concern, to re-engineer the hierarchical structure of soft materials and to functionalize the materials are the two common approaches to achieve the functions. This requires the synergy of structures among different levels, which include the re-construction of the hierarchical structure of soft/SF materials at the mesoscale and or Mesoscopic Material Assembly (MMA), which is to add and bind some specific nanomaterials or molecule to the networks so as to acquire some additional functions without jeopardizing the original performance. In this talk, I will cover the principles and strategies of mesoscopic structural re-engineering and functionalization of SF

materials, which allows in the design and integration of high-performance bio-integrated devices for future applications in consumer, biomedical diagnosis, and human–machine interfaces.

SESSION BM09.04: Bio-Inspired Materials Based on DNA or Peptide Building Blocks
Session Chairs: Xiang Yang Liu and Tiffany Walsh
Tuesday Afternoon, November 27, 2018
Sheraton, 2nd Floor, Back Bay A

**1:30 PM *BM09.04.01**
**Colloidal Crystal Engineering with DNA—Creating a Genetic Code for Materials Design** Chad A. Mirkin; Northwestern University, Evanston, Illinois, United States.

The materials-by-design approach to the development of functional materials requires new synthetic strategies that allow for material composition and structure to be independently controlled and tuned on demand. Although it is exceedingly difficult to control the complex interactions between atomic and molecular species in such a manner, interactions between nanoscale components can be encoded, independent of the nanoparticle structure and composition, through the ligands attached to their surface. DNA represents a powerful, programmable tool for bottom-up material design. The Mirkin Group has shown that DNA and other nucleic acids can be used as highly programmable surface ligands ("bonds") to control the spacing and symmetry of nanoparticle building blocks ("atoms") in structurally sophisticated materials, analogous to a nanoscale genetic code for material assembly. The sequence and length tunability of nucleic acid bonds has allowed us to define a powerful set of design rules for the construction of nanoparticle superlattices with more than 30 unique lattice symmetries, spanning over one order of magnitude of interparticle distances, with several well-defined crystal habits. Further, this control has enabled exploration of sophisticated symmetry breaking processes, including the body-centered tetragonal lattice as well as the clathrate lattice, the most structurally complex nanoparticle-based material to date (>20 particles per unit cell). The nucleic acid bond can also be programmed to respond to external biomolecular and chemical stimuli, allowing structure and properties to be dynamically tailored. Notably, this unique genetic approach to materials design affords functional nanoparticle architectures that can be used to catalyze chemical reactions, manipulate light-matter interactions, and improve our fundamental understanding of crystallization processes.

**2:00 PM BM09.04.02**
**DNA-Programmed Assembly of Single Crystalline Nanoparticle Superlattices at Interfaces** Robert J. Macfarlane; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

The programmability of DNA makes it an attractive structure-directing ligand for the assembly of nanoparticle superlattices with unique structure-dependent physical phenomena. While DNA base pairing has enabled the development of materials with nanometer-scale precision in nanoparticle placement and independent control over particle size, lattice parameters, and crystal symmetry, manipulating the macroscopic shape of the lattices remains challenging. By pairing this "bottom-up" assembly method with "top-down" lithographic techniques and assembling nanoparticle superlattices on a patterned substrate, complete control over crystal size, shape, orientation and unit cell structure can be realized. The key challenges in developing this technique are to first understand how different design factors affect the assembly process in this broken-symmetry system that is assembled at an interface, and subsequently develop structure-property relationships that correlate the above mentioned design parameters with the resulting overall material structure. Here, we examine both at-equilibrium deposition processes capable of generating single crystals with well-defined shapes, as well as post-deposition annealing to transform disordered particle arrangements into crystalline arrays. Using a combination of X-ray diffraction and electron microscopy techniques, both surface morphology and internal thin film structure are examined to provide an understanding of the mechanisms of particle crystallization under conditions where crystal growth is anisotropic due to a boundary condition. This novel method for controlling particle assembly draws several strong analogies to traditionally atomic epitaxy/heteroepitaxy, providing a useful tool for understanding thin film growth processes. As a result, we are able to realize 3D architectures of arbitrary domain geometry and size, thereby making materials with unprecedented precision across multiple length scales.

**2:15 PM BM09.04.03**
**Programmable DNA-Semiconductor Nanostructures for Molecular Delivery** Libing Zhang; Leslie Dan Faculty of Pharmacy, University of Toronto, Toronto, Ontario, Canada.

Biotemplated nanomaterials offer great promise in multimodal imaging, biosensing, and molecular delivery. There remains an unmet need for traceable and biocompatible nanomaterials that can be synthesized in a precisely controllable manner. Here, we demonstrate a single-step fabrication method for Quantum Dot-DNA Hydrogels and their successful application in enzyme-responsive drug/siRNA delivery and cell-specific targeting, and the use of a new family of materials – programmable metal/semiconductor nanostructures – for drug delivery and mRNA sensing in drug-resistant cells.

**2:30 PM BM09.04.04**
**Magnesium Stabilized Multifunctional DNA Nanoparticles for Tumor-Targeted and pH-Responsive Chemotherapy** Leilei Tian; South University of S&T of China, Shenzhen, China.

Functional nucleic acids, that can target cancer cells and realize stimuli-responsive drug-delivery in tumor microenvironment, have been widely applied for anti-cancer chemotherapy. The high cost, unsatisfactory biostability, and complicated fabrication process are the main limits for the development of DNA-based drug-delivery nanocarriers. Recently, a kind of DNA-MgPPi (magnesium pyrophosphate) composite nanoparticles has been produced from rolling circle amplification (RCA), which combine advantages of the designable and high-throughput isothermal amplification technique and the high stability of DNA condensation structures, quickly becoming an attractive biomedical material with great potentials. Herein, instead of using MgPPi, we found that only $Mg^{2+}$ is sufficiently enough to stabilize the functional DNAs for chemotherapeutic applications. The very long single-stranded RCA product with a high charge density is more prone to form a stable condensation structures compared with a short oligonucleotide. Moreover, the dynamic electrostatic interactions between $Mg^{2+}$ and DNA can better preserve the functions of DNA, which is more suitable for the design of drug-delivery system. A tumor-targeting Dox-delivery nanoparticle (~ 100 nm) was synthesized by the condensation of RCA products in the presence of an excessive amount of $Mg^{2+}$, which showed good bio-stability in serum, considerable Dox loading capability, specific cancer-targeting ability, and pH-responsive sustained Dox release.

The DNA nanoparticle not only has a simple composition, but also it will keep intact after the excessive exterior $Mg^{2+}$ is removed, making it safe and ideal for *in vivo* application. Through cellular and *in vivo* experiments, we thoroughly demonstrated that this kind of $Mg^{2+}$ stabilized multi-functional DNA nanoparticles can successfully realize tumor-targeted Dox delivery.

**2:45 PM BM09.04.05**
**DNA-Programmable Nanoparticle Lattices Assembled on Polymer-Patterned Surfaces** Sha Sun[1, 2], Dmytro Nykypanchuk[2], Gregory Doerk[2], Charles Black[2], Oleg Gang[2, 3] and Diana Lopez[2]; [1]Xi'an Jiaotong University, Xi'an, China; [2]Center of Functional Nanomaterials, Brookhaven National Laboratory, Upton, New York, United States; [3]Department of Chemical Engineering, Columbia University, New York, New York, United States.

Photonic and electronic devices require precise control of functional components at the nanosacle. The development of DNA nanotechnology offers a fascinating platform to direct the assembly of nanoparticles into well-organized architectures with prescribed distances and spatial arrangements. Here, we combine DNA-based assembly and diblock copolymer self-assembly to realize the multi-layer assembly of gold nanoparticles into large-area, three-dimensional arrays. Specifically, the assembly of gold nanoparticles is directed through binding with DNA origami that forms arrays, and the array growth is controlled by patterns formed via diblock copolymer on the surface. In our approach, DNA-programmable nanoparticle lattices are sequentially assembled with registry of polymer pattern. We show the potential to assemble functional nanoparticles in layer-by-layer manner with controllable interlayer distance and in-plane arrangements through a combination of surface patterns and DNA nanostructures.

**3:00 PM BREAK**

**3:30 PM *BM09.04.06**
**Engineering Molecular Assembly for 3D Electronics** Thom LaBean, Nikolay Frick and Ming Gao; North Carolina State University, Raleigh, North Carolina, United States.

The ability to design and program complex molecular interactions between synthetic biomolecules (especially polynucleotides and polypeptides) has led to a revolution in artificial nanomaterials capable of self-assembly. For example, DNA-based nanotech entails the design of artificial nucleotide sequences capable of self-assembling into desired geometric shapes and patterns with nanometer-scale precision. These synthetic DNA nanostructures have been shown useful for organizing other materials including inorganic nanoparticles (metals and semiconductors), nucleic acid aptamers, and carbon nanostructures. We are working with DNA self- and directed-assembly to develop a general purpose molecular assembly toolbox useful for a wide variety of applications, especially in nanoelectronics and medicine. One promising future direction is the bottom-up fabrication of electronics components and devices including molecular assembly of wires and metal nanoparticles toward the construction of single-electron transistors, multicomponent devices, and artificial neural networks.

**4:00 PM BM09.04.07**
**Self-Assembled Peptide Nano-Materials for Optics and Electronic Applications** Sharon Gilead and Ehud Gazit; Tel Aviv University, Department of Molecular Microbiology and Biotechnology, Tel Aviv, Israel.

In recent years, a key direction in the field of electronics and electro-optics involves the transition from inorganic to organic components, including organic light emitting diodes (OLED), thus paving the way towards flexible and wearable electronic and light emitting devices. Bio-inspired organic materials may be the next-generation of organic optoelectronic devices based on self-organization principles, which allow facile synthesis, eco-friendliness, resistance to oxidation and no need for heavy metal doping.
Recent advances in bioorganic nanotechnology have established the notion that very simple building blocks, such as dipeptides, can form regular nanostructures with distinct mechanical, optical, piezoelectric and electronic properties. In particular, members of the diphenylalanine (FF) peptide archetypical family have been shown to form various morphologies and ordered nanostructures such as tubes, rods, fibrils, spheres, plates and macroscopic hydrogels with nano-scale order.
Several studies have explored the piezoelectric properties of the diphenylalanine (FF) peptide. In the presence of an external electric field, vertically aligned FF microrod arrays can be organized on a substrate, resulting in enhanced piezoelectric response.
Here we show the ability of FF and other similar peptide assemblies to be used in various electronics and optics application as new bioorganic materials. FF assemblies can act as an active optical waveguiding material, allowing locally excited states to propagate along the axis of the assemblies. In addition, Fmoc capped building blocks exhibit remarkable optical properties, such as quantum confinement and fluorescence. Other rod-like assemblies and toroid-like assemblies exhibit remarkable physicochemical features, including high thermal stability, metallic-like mechanical rigidity, luminescence, piezoelectricity and semi-conductivity.
The ability of FF to self-assemble into ordered structures was discovered by a systematic reductionist exploration of biological recognition modules in an amyloidogenic polypeptide. We are applying a similar reductionist approache to expand our search for minimal building blocks towards single amino acids as well as other metabolites such as nucleobases, demonstrating their self-assembly into various ordered structures. Doing this we are enlarging our library of biological building blocks which bear the potential to be novel bio-inspired supramolecular materials for Optics And Electronic applications.

**4:15 PM BM09.04.08**
**Amino Acid-Encoded Biocatalytic Self-Assembly for Transient Functional Nanostructures** Mohit Kumar and Rein Ulijn; Nanoscience, ASRC, City University of New York at the Graduate Center, New York, New York, United States.

One key feature of biological systems is the existence of chemically fueled, transient structure and function, like the on-demand formation/degradation of tubulin, actin fibers etc. Supramolecular polymers as synthetic mimic of such biomaterials has shown great promise in a number of areas, including biomedicine, sensing and energy harvesting. However, the main challenge is to actively regulate the shape, function and performance of these materials, while maintaining constant, physiological conditions. This has inspired recent research towards temporal control of nanostructures, which is achieved by using (bio-)catalysis to activate building blocks and thereby drive assembly. In this regard, potential for design of active supramolecular nanostructures based on peptide nanotechnology is increasingly appreciated. The objective of this work is demonstration of active encoding of nanostructures by using simple amino acids, resulting in transient conducting nanowires and *in situ* visualize time dependent dynamics of such structure.

We designed a self-assembling core molecule with two in-built competing reactive sites, consisting of the organic semiconductor naphthalenediimide (NDI), conjugated with *D* and *L* enantiomer of tyrosine methyl esters.[i] The stereoselective fast enzymatic reaction at the *L* enantiomer compared to the *D* enantiomer provides the necessary kinetic competition to achieve temporal control over assembly. By simply adding one of a range of encoding amino acids in the presence of enzyme α-chymotrypsin, we achieve pathway selection between hydrolysis and acylation at both chiral ends. This results in an *in situ* modification of the amphiphilic structures, giving rise to unique self-assembly trajectories that are time programmed by the nature of encoding

amino acid. Taking advantage of the semiconducting nature of the NDI core, electronic wires could be formed and subsequently degraded, resulting in temporally regulated electro-conductivity. Such a system holds great promise towards interfacing biology with electronics. Moreover, by appropriately functionalizing molecules with a fluorophore, the dynamic formation and degradation of nanofibers could be visualized with STED (Stimulated Emission Depletion microscopy) based super resolution microscopy. Such imaging significantly improved the resolution (39%) compared to traditional confocal. Interestingly, the lifetime of transient nanostructures can be completely controlled by simply choosing different amino acids. Overall, the biocatalytic incorporation of encoding amino acids around a functional core offers a general approach to modulate, switch or fine-tune supramolecular structures over time which can now be visualized *in situ* with superresolution microscopy.

[i] M. Kumar, N. Ing, V. Narang, N. Wijerathne, A. Hochbaum, R. V. Ulijn, *Nat. Chem.*, 2018, **10**, 696.

**4:30 PM BM09.04.09**
**DNA Origami-Assembled Light-Emitting Nanoclusters with Controllable Optical Output** Honghu Zhang[1], Mingxing Li[1], Kaiwei Wang[1, 2], Ye Tian[1], Jia-Shiang Chen[1], Mingzhao Liu[1], Katherine T. Fountaine[3], Donald DiMarzio[3], Mircea Cotlet[1] and Oleg Gang[1, 4]; [1]Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, New York, United States; [2]School of Science, Xi'an Jiaotong University, Xi'an, China; [3]NG Next, Northrop Grumman Aerospace Systems, Redondo Beach, California, United States; [4]Department of Chemical Engineering and Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York, United States.

Structural DNA nanotechnology has emerged as a powerful method to fabricate targeted nanoscale architectures. Using rationally designed DNA origami frames, nanoparticles can be coordinated in a prescribed manner in 3D. Here, we have designed DNA origami frames for assembling various nanoparticles in pre-determined locations. The DNA frames have enabled well-defined nanocluster assembly with nanometer-precision positioning, and controllable high-purity stoichiometry with tunable functionality. We have fabricated DNA origami-constructed nanoparticle clusters, consisting of spherical quantum dots (QDs) and gold nanoparticles (AuNPs) that exhibit controllable photoluminescence (PL) when the excitation wavelength is close to surface plasmon resonance of the AuNPs. Furthermore, these self-assembled nanoclusters emit highly polarized light. By varying the size and number of AuNPs in the nanoclusters, we have explored correlations between the assembled structures and the PL polarization magnitude and the overall PL enhancement. Our DNA origami based nanoclusters with precisely built 3D architectures provide an efficient route to control single emitter optical output.

**4:45 PM BM09.04.10**
**Reconfigurable Nanoparticle Superlattices with Tunable DNA Bonds** Jinghan Zhu, Youngeun Kim, Haixin Lin, Shunzhi Wang and Chad A. Mirkin; Northwestern Univ, Evanston, Illinois, United States.

Stimuli-responsive nanomaterials with reconfigurable structures and properties have garnered significant interest in the fields of optics, electronics, magnetics, and therapeutics. DNA is a powerful and versatile building material that provides programmable structural and dynamic properties, and indeed, sequence-dependent changes in DNA have already been exploited in creating switchable DNA-based architectures. However, rather than designing a new DNA input sequence for each intended dynamic change, it would be useful to have one simple, generalized stimulus design that could provide multiple different structural outputs. In pursuit of this goal, we have designed, synthesized, and characterized pH-dependent, switchable nanoparticle superlattices by utilizing i-motif DNA structures as pH-sensitive DNA bonds. When the pH of the solution containing such superlattices is changed, the superlattices reversibly undergo: (i) a lattice expansion or contraction, a consequence of the pH-induced change in DNA length, or (ii) a change in crystal symmetry, a consequence of both pH-induced DNA “bond breaking” and “bond forming” processes. The introduction of i-motifs in DNA colloidal crystal engineering marks a significant step toward being able to dynamically modulate crystalline architectures and propagate local molecular motion into global structural change via exogenous stimuli.

SESSION BM09.05: Poster Session I: Bioinspired Materials
Session Chairs: Chun-Long Chen and Tiffany Walsh
Tuesday Afternoon, November 27, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

**BM09.05.01**
**Tandem Molecular Self-Assembly in Liver Cancer Cells** Jie Zhan[1], Yanbin Cai[1], Ling Wang[2] and Zhimou Yang[1]; [1]College of Life Sciences, Nankai University, Tianjin, China; [2]College of Pharmacy, Nankai University, Tianjin, China.

Inspired by nature, stimuli-responsive self-assembly has been widely explored for spatiotemporally regulating diverse cellular functions. *In situ* formation (both pericellular and intracellular) of assemblies of man-made small molecular in cell milieu has been successfully applied for controlling the cell behavior and fate. The differences of the expression levels of bio-signals (*i.e.*, enzyme or small molecule) between cells are favorable natural-source of inspiration for designing precursors to form sophisticated assemblies with enhancing selectivity to target and inhibit diseased cells. We herein describe the tandem molecular self-assembly of a peptide derivative NBD-GFFpY-ss-ERGD (Tandem Molecular Self-assembly Precursor, *TMSP*) that is controlled by a combination of enzymatic and chemical reactions. In phosphate-buffered saline (PBS), *TMSP* self-assembles first into nanoparticles by phosphatase and then into nanofibers by glutathione. Liver cancer cells exhibit higher concentrations of both phosphatase and GSH than normal cells. Therefore, the tandem self-assembly of *TMSP* also occurs in the liver cancer cell lines HepG2 and QGY7703; *TMSP* first forms nanoparticles around the cells and then forms nanofibers inside the cells. Owing to this self-assembly mechanism, *TMSP* exhibits large ratios for cellular uptake and inhibition of cell viability between liver cancer cells and normal liver cells. We envision that using both extracellular and intracellular reactions to trigger tandem molecular self-assembly could lead to the development of supramolecular nanomaterials with improved performance in cancer diagnostics and therapy.

**BM09.05.02**
**Fabrication and Evaluation of a Repairable Resistive Device Using Bio Material for a Synaptic Device** Takahiko Ban[1], Yukiharu Uraoka[2] and Shin-ichi Yamamoto[1]; [1]Ryukoku University, Otsu, Japan; [2]NAIST, Ikoma, Japan.

As our information society advances, the roles of semiconductor devices are becoming increasingly important. However, the total volume of data handled by humans is steadily expanding and becoming complex. The volume of data has been estimated to reach 44 zettabytes in 2020. Devices that can record and process large volumes of information are required for the benefit of society. However, in forthcoming practical nanoscale applications, the downsizing of the device reaches its limit. Therefore, it is necessary to develop new devices with different principles and structures. As one solution to expand the

scaling limit and to process information more flexibly, devices and/or circuits that simulate a human brain have gained attention. Simulating a human brain in computers is expected to enhance recognition capability and reduce power consumption. Research on devices reproducing synapses, which transmit information, is attracting particular attention. Neural networks in the human brain comprise neurons connected with each other through synapses. A synapse connects neurons upon receiving a stimulus; the weaker the stimulus, the weaker the connection. Resistive memory has been proposed as a circuit capable of simulating a synapse. In this research, resistive switching memories (ReRAM) were fabricated for synaptic devices. By applying repair capacity to the ReRAM, the resistance value is returned to original value over time under low bias. In addition, the ReRAM are fabricated with nanoparticles (NPs) using biomaterials. The biomaterial is a spherical shell protein called ferritin. It has the ability to precipitate inorganic substances as NPs in the internal cavity, and various placement methods can be provided by modifying its surface. In this study, a method is adopted in which NPs are evenly arranged at intervals of 40 to 50 nm by modifying PEG on the surface of ferritin.
A tantalum oxide ($Ta_2O_5$) film was deposited on the lower electrode deposited by electron beam deposition (EB depo.), and the upper electrode was similarly deposited to fabricate a usual ReRAM. A structure in which manganese oxide ($MnO_2$) was sandwiched between the $Ta_2O_5$ film and the lower electrode was fabricated to prepare a ReRAM having repairing capability. In this device, we succeeded in developing a device that returns to the original high resistance state with low bias voltage and time. It is short-term plasticity well-known as synaptic movement. Also, manganese oxide is nanoparticulated by ferritin. The resistance change phenomenon, which is a complex analog operation, is limited to only nanoparticles. By preparing this device, it is expected to mimic the work of actual synapses which exist in tens of thousands among neurons.

**BM09.05.03**
**Surface Interactions of DNA and Mononucleotides with Sol-Gel Derived Silica Host** Derya Kapusuz[2] and Caner Durucan[1, 3]; [1]METU, Ankara, Turkey; [2]Gazinantep University, Gaziantep, Turkey; [3]BIOMATEN, Ankara, Turkey.

Double stranded DNA and dAMP (2′-Deoxyadenosine 5′-monophosphate) were encapsulated in silica by sol-gel route. The microstructure of the biomolecule-hostings gels and the chemical interactions between biomolecules and silica host have been investigated. Ethidium bromide (EtBr) intercalation and leach out tests showed revearled a high hydraulic reactivity for encapsulated DNA and dAMP gels due to presence of more silanol groups than plain silica gel. For both biomolecules, no chemical binding occurred with Si core of the silica network. The chemical association between DNA/dAMP and silica host was through phosphate groups and molecular water attached to silanols, acting as a barrier around biomolecules. The helix morphology was found not to be essential for such interaction. BET analyses showed that interconnected, inkbottle shaped mesoporous silica network with an average pore size of 5.6 nm for DNA and 4.8 nm for dAMP containing bulk gels, respectively.

**BM09.05.04**
**Bio-Inspired Thin-Film Deposition of ZnO Nanocrystals** Naomi Kramer, Ofir Friedman, Yuval Golan and Nurit Ashkenasy; Department of Materials Engineering and the Ilse Katz Institute for Nanoscale Science and Technology, Ben-Gurion University of the Negev, Beer-Sheva, Israel.

ZnO, a high mobility *n*-type semiconductor, is a highly attractive transparent material for applications in optoelectronic devices. However, the manufacture of high quality ZnO thin films requires high temperatures and/or pressure, making the processes expensive. **In this work we will demonstrate a biomimetic approach for the synthesis and deposition of ZnO films on Si substrates under mild ambient conditions.** Simultaneous synthesis and deposition of ZnO nanoparticles (NPs) is achieved in this work by the use of dual affinity peptides (DAPs) as linkers. One segment of the DAP has a strong affinity to the substrate and the other promotes the synthesis of the NPs. The formation of 10-20 nm crystalline NPs in solution is confirmed by transmission electron microscope (TEM) electron diffraction analysis. Further X-ray photoelectron spectroscopy (XPS) and energy dispersive spectroscopy (EDS) characterization revealed 1[Zn]:1[O] stoichiometry. Initial results demonstrating the *in-situ* deposition of ZnO NPs on Si using the DAP linkers will also be presented. We will further show that the DAP monolayers reduce the work function of ZnO by ~260 meV. This work demonstrates the great potential of using low-cost and green biomimetic approaches for the fabrication of thin nanocrystalline inorganic films towards implementation in optoelectronic devices.

**BM09.05.05**
**Fabrication of Composite Coatings for Drug Delivery Using Bile Acid Salts** Amanda Clifford and Igor Zhitomirsky; Materials Science and Engineering, McMaster University, Hamilton, Ontario, Canada.

A conceptually new fabrication technique has been developed for the fabrication of composite gel coatings containing commercially available drugs that exhibit low solubility in water. This technique utilizes bile acid salts, which are natural anionic biosurfactants, that have powerful solubilizing properties; these can be used for the dispersion of organic molecules, dietary fat and vitamins in mammalian digestive systems. This work is of paramount importance, as 40% of commercially available drugs and 90% of drugs being developed exhibit low solubility in water. Bile acid salts have also been found to form unique porous gel structures, which is advantageous for tissue scaffold applications. In the present work, bile acid salts were used for the solubilization, dispersion, charging and composite film formation using anodic electrophoretic deposition (EPD). Ibuprofen, which is a commercially available non-steroidal anti-inflammatory drug, and tetracycline, a clinically used anti-biotic were used as model water-insoluble drugs. Cholic acid sodium salt and deoxycholic acid sodium salt were used as model bile acid salts. In our method, bile acid salts dissolved in an aqueous suspension solubilized our model water-insoluble drugs to form charged mixed micelles. Under the influence of electric field, the mixed micelles electromigrate to the anode surface, where the carboxylic groups of the bile acid salts become protonated and form an insoluble film on the electrode surface. Composite films were obtained by potentiodynamic and galvanostatic deposition methods. The cyclic voltammetry and quartz crystal microbalance data provided an insight into the deposition mechanism and kinetics of deposition at various conditions. X-ray analysis confirmed the formation of composite films. SEM investigations of pure bile acid films and composites revealed the influence of the co-deposited drugs on film microstructure. The composite coatings were deposited as functionally graded materials or laminates for controlled drug delivery. This work offers a versatile approach for the deposition and delivery of drugs, which have poor solubility in water. We demonstrate that new EPD strategies pave the way for the fabrication of composite films containing drugs and other advanced functional biomaterials. These films may be used for a variety of applications: from tissue scaffolds to orthopaedic coatings.

**BM09.05.06**
**Surface-Induced Self-Assembly for Fluorescence and Visual Detections of Enzyme Activity in Complex Environments** Tengyan Xu and Zhimou Yang; Nankai University, Tianjin, China.

Self-assembly is widespread in nature. Supramolecular hydrogels formed by small molecular pepetides that self-assemble in water through the noncovalent interactions have the advantages of simple chemical synthesis, easy modification of component units, good biocompatibility and low toxicity, and fluorescence probes have been applied for the detection of important analytes with high sensitivity and specificity. However, they cannot be directly applied for the detection in samples with auto-fluorescence such as blood.
Herein, we demonstrated a simple but effective method of surface-induced self-assembly/hydrogelation for fluorescence detection of an enzyme. First, the peptide precursor NBD-FFpY with fluorescent group NBD was synthesized by solid-phase synthesis method. Then NBD-FFpY could be dephosphorylated

to form gelators NBD-FFY by alkaline phosphatase. After the peptide precursor NBD-FFpY was cleaved by the alkaline phosphatase, NBD-FFY can be enriched on the surface of positively charged glass plate. Therefore, the enzymatic concentration can be calculated through detecting the fluorescent intensity of NBD-FFY on the glass surface. We also found that the fluorescent intensity of NBD-FFY deposited on the surface of the glass was linearly related to the incubation time and the concentration of the enzyme. Even in the complex environments such as blood and cell lysate, our method can still quickly detect the activity of the enzyme.
As a result, surface-induced self-assembly for fluorescence not only expands the application of molecular selfassembly but also provides a useful method that can be applied for direct detection of enzyme activity in complex biological samples such as blood and cell lysates.

**BM09.05.07**
**Studies on Synthesis and Fluorescence Spectroscopy of Hybrid Magnetic Nanoparticles ($Fe_3O_4$-Au) Linked with Fluorescent Molecule** Alisha Memon[1], Andrew Nunez[1], Mostafa Sadoqi[1], Elmustapha Feddi[2] and Gen Long[1]; [1]Saint John's University, Jamaica, New York, United States; [2]Group of Optoelectronic of Semiconductors and Nanomaterials,, ENSET, Mohammed V University, Rabat, Morocco.

Magnetic and fluorescent nanoparticles are widely studied in biomedical research for their use in drug delivery, cell separation, magnetic resonance imaging (MRI), hyperthermia, various multimodal techniques, etc. In this study, we report a recent work on nanoparticles incorporating with a fluorescent molecue and a superparamagnetic core via nanoscale engineering. $Fe_3O_4$-Au hybrid nanoparticles are synthesized via a solution phase chemical reaction in an inert $N_2$ atmosphere. These synthesized hybrid nanoparticles are characterized by UV-Vis-NIR spectroscopy, fluorescence spectroscopy, XRD, TEM, etc. Optimal synthesis conditions are also highly relevant in producing stable and uniform hybrid nanoparticles without impurities. Fluorescence spectroscopy show the correlations between the lifetime and intensity of fluorescence and sizes, compositions, shapes of hybrid nanoparticles as well as the conjugation process to link the nanoparticles to fluorescent molecules. By carefully engineering the growth conditions, such as altering growth temperatures and precursor reagent ratios, functional hybrid magnetic nanoparticles can be optimized for hyperthermia, MRI and other multimodal biomedical applications.

**BM09.05.08**
**Self-Assembly of Peptoids with Polyoxometalates into Nanostructured Materials** Lei Wang[1, 2] and Chun-Long Chen[1]; [1]Pacific Northwest National Laboratory, Richland, Washington, United States; [2]Jiangxi Normal University, Nanchang, China.

Polyoxometalates (POMs) are one of the structurally-characterized anionic oxide nanoclusters that have been frequently used as building blocks to self-assemble organic-inorganic hybrid materials. POMs-based hybrid materials have received attractive attention owing to their applications in catalysts, photovoltaics, molecular magnetism, and biochemistry.
Peptoids, a type of sequence-defined synthetic molecules, are composed of repeating N-substituted glycine monomer units and developed as attractive protein-mimetics to combine the advantages of both synthetic polymers and biopolymers. Moreover, peptoids are more thermally and chemically stable in comparison with peptides and proteins. The lack of both intra- and intermolecular backbone hydrogen bonds make peptoids as unique building blocks for controlled self-assembly[1-4] and tuning the function of peptoid-based materials.[5] In this presentation, we will report the two alternative approaches to self-assemble organic-inorganic hybrid materials from POMs and peptoids. For the first approach, peptoids containing cationic residues are co-assembled with anionic POMs via electrostatic interaction. Peptoid sequences and the ratio of POMs and peptoids are varied to tune the morphology of the self-assembled hybrid materials. The second approach is based on building POM-containing peptoids by having POMs as peptoid side chains, then these hybrid sequences are self-assembled into hierarchically-structured organic-inorganic hybrid materials. Comparing to the first approach, the second approach offers the precise control the location and stereochemistry of POMs within peptoid assemblies.
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(3) Jin, H.; Jiao, F.; Daily, M. D.; Chen, Y.; Yan, F.; Ding, Y.-H.; Zhang, X.; Robertson, E. J.; Baer, M. D.; Chen, C.-L. Highly stable and self- repairing membrane-mimetic 2D nanomaterials assembled from lipid-like peptoids. *Nat. Commun.* **2016**, *7*, 12252.
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**BM09.05.09**
**Mineral-Assisted Self-Assembled Nanostructures from Poly-Glycine, Hydrogels of Short Peptides and Alpha-Hydroxy Acids** Rehana Afrin[1], Tony Jia[1], James Cleaves[1], Taka-aki Yano[2] and Masahiko Hara[2, 1]; [1]Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan; [2]School of Materials and Chemical Technology, Tokyo Institute of Technology, Yokohama, Japan.

The principle of self-assembly is fundamental in the formation of higher order structures from small molecules. Many kinds of such structures have been formed from small amino acids and short peptides as useful materials for bio-medical purposes [1]. They also have a fundamental importance as the starting ingredients for the creation of life on the Earth. From this point of view, we first studied the adsorption mechanism of amino acids and peptides to solid surfaces [2] and proceeded to investigate the formation of self-assembled structures in solution and on solid surfaces. In this study, we present the formation of new types of self-assembled structures of poly-glycine, short peptides and alpha-hydroxyacids and show their interesting structural properties obtained with the atomic force microscope (AFM).
Poly-glycine is water insoluble but soluble in tetrafluoroacetic acid (TFA). Dilution of its TFA solution with deionized water led to the formation of small self-assembled structures. AFM observation revealed the formation of thin and flat films (1 – 2 nm thick and 200 – 500 nm wide) and isolated fibers (10 – 50 nm wide). Because poly-Gly does not have charges except for at its N- and C-termini, some types of rather strong non-ionic attractive force, most likely involving van der Waals force, must be working at the basic level. The thickness of the film implies an alignment of a few poly-Glycine helices in the vertical direction and many of them into an ordered side-side arrangement. Such a uniformly flat structure suggests its possible role as a reliable and well defined platform for further assemblage with other molecules as a composite film.
We also found that some short peptides and alpha-hydroxy acids self-assembled into long strings as well as a hydrogel structure under an aqueous condition at specific pHs. The hydrogel has a nano-mesh like structure that can be reconstructed on mineral surfaces and visualized with AFM. We are particularly interested in possible roles of these structures as potential functional biomaterial in the origin of life on the Earth.

**BM09.05.10**
**Catalytic Self-Assembly of Peptidic Bolaamphiphiles Coordinated with Transition Metal Cofactors** Sang-Yup Lee, Min-Chul Kim and Changjoon Keum; Yonsei Univ, Seoul, Korea (the Republic of).

Peptidic bolaamphiphile is an biomimetic amphiphilic molecule whose biochemical activity can be tuned by the designer peptides. The peptidic bolaamphipihles have peptide or amino acid segments as hydrophlic moieties that are associated with the central alkyl chain to display amphiphilic property. Similar to other amphiphilic molecules, these peptidic bolaamphiphiles self-assemble to form complex structures while exposing the biological segment to the surface in an aqueous medium. Here, assembled structure of histidyl bolaamphiphiles was exploited as a biomimetic host matrix whose histidine imidazoles are exploited as ligands to coordinate with transition metal ions. By coordinating with transition metal ions, metalloenzyme-mimetic catalysts could be built. In particular, catalytic activity for CO2 hydration and oxidation of organic compounds could be realized by coordinating various transition metal ions to the histidyl bolaamphiphile assembly. Furthermore, the catalytic water evolution was achieved by introducing Iridium to the histidyl bolaamphiphile assembly. The prepared metal-bolaamphiphile catalyst was surveyed with spectroscopic studies to verify the origin of the catalytic activity. This assembly of peptidic bolaamphiphiles will be beneficial for the building of catalysts mimicking various metalloenzymes.

**BM09.05.11**
**Thermodynamic Properties of Pluronic F127 Micelles with Added Cefepime Determined by Differential Scanning Calorimetry** Lydia M. Mensah[1] and Brian J. Love[1, 2]; [1]Material Science and Engineering, University of Michigan–Ann Arbor, Ann Arbor, Michigan, United States; [2]Biomedical Engineering, University of Michigan–Ann Arbor, Ann Arbor, Michigan, United States.

Aqueous amphiphilic copolymer polyether solutions have been made with varying amounts of a third constituent with the notion of forming drug loaded gels. Our research group is interested in how additive molecules perturb the structure of amphiphilic copolymers that are known to form colloidal crystals. We are investigating whether likely correlations exist between how strongly the drug interacts within the hydrophobic and hydrophilic regions of micelles and colloidal crystals and how bioavailable the drug is as it elutes from within the gel. We have made 25% aqueous solutions of PEO-PPO-PEO copolymers (F-127, BASF) formulated and tested between -5ºC and 50ºC. Rheology, and DSC have been the primary tools of measurement and we have focused our initial efforts on cefepime to observe how its presence affects micelle formation and colloidal crystallization. Drug-loaded polymers are of interest as schemes within the drug delivery community for controlled release and other studies have been done using dendrimers, and responsive polymers contained within other polymers. We have found that when Cefepime has been added in concentrations ranging from 2-8% of the mass of a 25% PEO-PPO-PEO copolymer solution, the onset temperature for micelle formation systematically drops with increasing cefepime concentration. The change is not dramatic, 9.1ºC ±5.1 for neat, while 4.5ºC ±5.1 for 8%, the trend is apparent. The size of the endotherm does not show the same systematic trend and within the realm of statistical analysis, the size of the endotherm is invariant to cefepime concentration. At 2ºC/min, the energy of the gel formation is masked by the rest of the endotherm linked with micelle formation. We are testing a lower ramp rates in order to observe the transition linked with the gel. Separately we have resolved that the gel is clearly forming and requires a cold re-equilibration to break up the gel structure. It can be inferred that cefepime is acting as a chaperone to allows micelles to nucleate more easily at lower temperature. We will present on the gel formation temperatures, enthalpies, and transitions to show the structural formation and development of the other polymers-drug complexes beyond cefepime/F-127.

**BM09.05.13**
**β-Sheet Crystallization-Driven Supramolecular Peptide Nanoagents with Structure-Dependent Theranostic Functions** Inhye Kim[1, 2] and Eunji Lee[1]; [1]School of Materials Science and Engineering, Gwangju Institute of Science and Technology, Gwangju, Korea (the Republic of); [2]Graduate School of Analytical Science and Technology, Chungnam National University, Daejeon, Korea (the Republic of).

Versatile, one-dimensional (1D) supramolecular theranostic nanoagents were developed by β-sheet crystallization driven-assembly of peptide amphiphiles (PAs) attached with paramagnetic metal ion (gadolinium, $Gd^{3+}$)-chelating moiety and tumor cell-targeting segment, respectively. Paramagnetic metal-attached scaffolds have attracted much attention as magnetic resonance imaging (MRI) contrast agents (CAs). Many efforts have been devoted to enhance MRI efficacy of commercial CAs by adopting supramolecular scaffolds to overcome the disadvantages with low sensitivity and specificity. Here, fibrils, driven by the assembly of PA with hydrophobic β-sheet-forming peptide block, were utilized as a theranostic nanoscaffold with drug-loading within their robust core. The resulting 1D nano-aggregates allowed successful intracellular delivery of doxorubicin (DOX) to target cancer cells and contrast-enhanced MR imaging by high longitudinal ($T_1$) relaxivity of water protons. Correlation between the structural nature of fibrils formed by PA-assembly and its diagnostic efficacy was elucidated. The nanostructured theranostics with desirable functions may thus be a useful strategy for the generation of tailor-made biocompatible nanomaterials.

**BM09.05.14**
**Graphitization and Strength of Annealed Silks and Synthetic Polymer Fibers** Thomas Dugger[1], Sourangsu Sarkar[2], Sandra Correa-Garhwal[1], Mikhail Zhernenkov[3], Hourng Kim Chea[1], Cheryl Hayashi[4] and David Kisailus[1]; [1]University of California, Riverside, Riverside, California, United States; [2]Georgia Institute of Technology, Atlanta, Georgia, United States; [3]Brookhaven National Laboratory, Upton, New York, United States; [4]American Museum of Natural History, New York, New York, United States.

Silks have been proposed as superior carbon fiber precursors to synthetic polymers. β-sheet nanocrystals, the main contributor to silk's strength, have a favorable structure to graphitize upon annealing. Due to their uniform dispersion throughout the fiber and preferential alignment along the long axis of the fiber, silk-precursor carbon fiber could be stronger than traditional carbon fiber made from polyacrylonitrile (PAN). To investigate this theory, we compare the degree of graphitization, graphite crystal orientation, and tensile strength between spider silk, silkworm silk, PAN, and poly(vinyl alcohol).

**BM09.05.15**
**Fabrication of 2D Protein Films and 3D Protein Hollow Spheres via Alternative Self-Assembly of α-Synuclein and Their Applications** Soonkoo Lee[1], Ghibom Bhak[2] and Seung.R Paik[1]; [1]Chemical and Biological Engineering, Seoul National University, Seoul, Korea (the Republic of); [2]Organic Chemistry University of Santiago de Compostela (USC), Center for Research in Biological Chemistry and Molecular Materials (CIQUS), Santiago de Compostela, Spain.

Understanding the self-assembly process of amyloidogenic proteins is valuable not only to find their pathological implications but also to prepare protein-based biomaterials. α-Synuclein (αS), a pathological component of Parkinson's disease, producing one-dimensional (1D) amyloid fibrils, has been employed to generate two-dimensional (2D) protein films and three-dimensional (3D) protein hollow spheres (PHS) via its alternative self-assembly at either high temperature or rapid-freezing condition, respectively. At a high temperature of 50°C, αS molecules self-assembled into the 2D film whereas 1D amyloid fibrils were produced at 37°C. This alternative self-assembly phenomenon could be attributed to structural plasticity of the intrinsically disordered protein of αS which turns into a surface active agent at the air-water interface at the high temperature. The αS 2D film was also routinely prepared at the oil-water interface and used as a framework of molecular assembly to give rise to a polydiacetylene-based sensing material. 10,12-Pentacosadiynoic acids (PCDA) were aligned on the film in a spatially organized way and then photo-polymerized to induce the π-conjugated molecular assembly yielding blue color. Its colorimetric transition to red was induced by increasing temperature. This functionalized protein film increased its height to 60 nm from 40 nm upon the PCDA immobilization and exhibited enhanced physical and chemical stability. In addition, the modified film showed remarkable high electrical conductivity only in the red state. Under frozen condition, on the other hand, PHS were produced from αS oligomers via rapid freezing, frozen incubation,

and freeze-drying process. PHS prepared with αS-eosin conjugates and focused ion-beam severance of PHS confirmed their empty core structure. While PHS were stable at room temperature, they were immediately converted into amyloid burs comprised of protein nanofibrils upon heating. Therefore, PHS could be considered a constrained spherical structure transformable into biocompatible matrix material in nanoscale which could be used as a fill-in agent to improve mechanical strength of living tissues like skin as well as hydrogels in general. In this study, we have demonstrated selective fabrication of the amyloidogenic protein of αS into either 2D or 3D structures and their use as potential protein-based biomaterials.

**BM09.05.16**
**Chain-Like Superstructures of Macromolecular Micelles for Linear Assembly of Plasmonic Nanoparticles and Fluorophores** Kyungtae Kim, Sukwoo Jang, Jonghyuk Jeon, Donghwi Kang and Byeong-Hyeok Sohn; Seoul National Univ, Seoul, Korea (the Republic of).

In living organisms, we can find various chain-like structures in microscale, which are usually self-assemblies of biomacromolecules. For example, fibrils in a tissue consist of collagen as a biomacromolecular building block. Assemblies of collagens by controlled hydrogen bonding produce elongated supramolecular chains of fibrils. Similarly, colloidal nanoparticles having patches can be employed as effective building blocks for chain-like superstructures. Well-defined patches on nanoparticles can serve bonding parts for assembling process of linear chains. Especially, macromolecular micelles can have distinct patches on their surface so that they can be assembled into linear superstructures. In this presentation, we polymerized chain-like superstructures with patchy micelles of diblock copolymers and then utilized them for linear assembly of plasmonic nanoparticles and fluorophores. The growth of nanoparticles was controlled within the cores of macromolecular micelles in chain-like superstructures. In addition, fluorescent dyes were selectively attached to the core-forming blocks of macromolecular micelles to organize them into linear assemblies. We also produced red-, green-, and blue-emitting linear superstructures by varying the dyes attached to the core-forming block. We characterized optical properties of chain-like superstructures functionalized with plasmonic nanoparticles and fluorophores.

SESSION BM09.06: Biomineralization and Biomimetic Crystallization
Session Chairs: Nico Sommerdijk and Tiffany Walsh
Wednesday Morning, November 28, 2018
Sheraton, 2nd Floor, Back Bay A

**8:00 AM *BM09.06.01**
**Biomineralization-Inspired Self-Organized Organic/Inorganic Composites—Stimuli-Responsive Ordered Nanorod Materials and Aligned Thin Films Formed with Macromolecular Templates** Takashi Kato; The University of Tokyo, Tokyo, Japan.

Biomineralization-inspired synthesis of organic/inorganic composites has attracted attention. We have been developing a variety of composite materials based on macromolecular templates.[1] Here we report hydroxyapatite and calcium carbonate nanorod composites that exhibit liquid-crystalline properties and zinc oxide thin-films with controlled aligned structures.
The TEM observations of the nanorod composites show that they have crystalline structures covered with acidic macromolecules.[2.3] These nanorods exhibit colloidal liquid-crystalline states. Hydroxyapatite nanorod materials are aligned under application of an external magnetic field.[2] Magneto-optical response has been achieved for the liquid-crystalline states under crossed polarizers. Liquid crystalline materials are also obtained for calcite nanorods.[3] We have also applied bioinspired synthesis to the development of functional ZnO thin-film materials with oriented structures.[4] We have succeeded in the biomineralization-inspired synthesis of composite thin films comprising of zinc hydroxide carbonates that are not found in biominerals. The composite thin films are converted to ZnO thin films with ordered structures through thermal treatment.
Bioinspired syntheses are useful approaches to the development of new functional materials by low-energy consumption and environmentally friendly processes.
[1] Kato, T.; Sakamoto, T.; Nishimura, T. MRS Bull. 2010, 35, 127; Cantaert, B.; Kuo, D.; Matsumura, S.; Nishimura, T.; Sakamoto, T.; Kato, T. ChemPlusChem 2017, 82, 107.
[2] Nakayama, M.; Kajiyama, S.; Kumamoto, A.; Nishimura, T.; Ikuhara, Y.; Yamato, M; Kato, T. Nature Commun. 2018, 9, 568.
[3] Nakayma, M.; Kajiyama, S.; Nishimura, T.; Kato, T. Chem. Sci. 2015, 6, 6230.
[4] Matsumura, S.; Horiguchi, Y.; Nishimura, T.; Sakai, H.; Kato, T. Chem. Eur. J. 2016, 22, 7094.

**8:30 AM BM09.06.02**
**Utilizing GLC-TEM to Elucidate Magnetosome Biomineralization in Magnetotactic Bacteria** Emre Firlar[1, 2], Meagan Ouy[1], Agata Bogdanowicz[1], Leigha Covnot[1], Boao Song[2], Yash Nadkarni[1], Reza Shahbazian-Yassar[2] and Tolou Shokuhfar[1]; [1]Bioengineering, University of Illinois at Chicago, Chicago, Illinois, United States; [2]Mechanical and Industrial Engineering, University of Illinois at Chicago, Chicago, Illinois, United States.

Biomimicking of $Fe_3O_4$ magnetosome synthesis ex situ is of interest due to the potential uses in the physical and medical field, and is thus important to understand the biomineralization pathway for the magnetosomes in magnetotactic bacteria. Conventional TEM approaches use fixation of bacteria preventing monitoring the dynamics or using fluid cell TEM holder which does not have enough spatial resolution. Therefore, in this work, graphene liquid cells (GLC) were used to encapsulate magnetotactic bacteria after mixing them with iron rich growth medium, thus maintaining the native environment. For the first time, the formation of these nanoparticles and increased nanoparticle contrast due to advancing biomineralization using GLC-TEM was monitored.

Through electron energy loss spectroscopy (EELS) analysis, the presence of graphene optical gap, water exciton peak and graphene $\sigma+\pi$ bond were monitored at 6 eV, 8.5 eV and at 14eV, respectively. Formation of radiation induced $H_2$ bubbles and magnetosomes were observed as well, indicating the presence of liquid during electron imaging. $Fe^{2+}$ (octahedral), $Fe^{3+}$(tetrahedral), $Fe^{3+}$ (octahedral) and FeOOH reference spectra were used to fit the experimental data. Relative ratio of $Fe^{2+}$ to $Fe^{3+}$ was calculated to be 0.35. Magnetite was known to be able to be converted to first maghemite and then to hematite via the electron beam exposure. Considering this ratio will be 0.5 for a perfect $Fe_3O_4$ (1x $Fe^{2+}$, 2x $Fe^{3+}$), hematite is the strongest candidate to be present in addition to magnetite in magnetosomes contributing to higher $Fe^{3+}$ content. At different time scales after iron induction, (i) an increase of the magnetosome image contrast was reported by the line profile drawn across the magnetosome and increased TEM contrast showed increased mass-thickness in the image, which indicates progression in biomineralization and incorporation of more $Fe_3O_4$ molecules to this particle; and (ii) an increase in the number of magnetosomes were observed.

**8:45 AM BM09.06.03**

**The Formation of Macromolecular Silica Nanocomposites Through Self-Assembly and Biomineralization** Paula Vena, Demi de Moor, Heiner Friedrich, Joseph P. Patterson and Nico Sommerdijk; Department of Chemical Engineering and Chemistry, TU Eindhoven, Eindhoven, Netherlands.

In nature we can find many examples of organic-inorganic nanocomposites with exceptional properties. For example, diatoms are unicellular algae whose cell walls are formed form hierarchical nanostructured silica. *Euplectella sp*. is a siliceous sponge that can assemble a mechanically resistant glass cage with nano- to macro- hierarchical organization. In both cases the formation process occurs by the intricate interactions between macromolecules and the silica precursors. These beautiful examples provide inspiration for the controlled formation of structurally complex silica based materials under ambient conditions.

In this paper we present a detailed study on the use of synthetic macromolecules to control silica morphology using two strategies: 1) mineralization of silica in pre-assembly macromolecular templates with defined pores and 2) the co-assembly of silica precursors and nanoparticles with macromolecules. Using (cryo)-electron microscopy, (cryo)-electron tomography and liquid phase electron microscopy we investigate the formation processes and characterize the hierarchically porous silica structures.

We discuss the underlying principles of silica mineralization in confinement and design strategies for making hierarchically porous silica based materials. Such porous materials have many potential applications including insulators, sensors, catalysts and drug delivery vehicles. We hope the insights provided by our detailed investigation will help towards the rational design and understanding of mechanisms formation of porous silica based materials.

**9:00 AM BM09.06.04**
**Mineralization in Bio-Inspired Metal-Coordinate Polymer Hydrogels** Niels Holten-Andersen; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Biominerals have been widely studied in part due to their unique mechanical properties, afforded by their inorganic-organic composite structure and well-controlled growth in macromolecular environments. More recently, growing concerns over climate change and environmental sustainability and the emerging relevance of green chemistry make biomineralization an even more attractive process to study. Here, we focus on the earlier stages of mineral nucleation and growth in macromolecular environments, where an organic, hydrogel matrix dominates the bulk properties of the material and the mineral is distributed throughout the matrix as nano- and/or microparticles. The phase, morphology, and size of the particles can be controlled using the choice of the hydrogel, functional moieties on the gel polymer backbone and soluble additives. Depending on the choice of organic matrix and inorganic mineral, the matrix can be dissolved to leave highly uniform particles, or the matrix can be left intact, creating a hydrogel-mineral composite with improved mechanical properties through organic-inorganic interfacial interactions or additional functionality, such as magnetic properties.

**9:15 AM BM09.06.05**
**Towards Templating 2D Magnetite Platelets via Bio-Inspired Approaches** Bernette Oosterlaken[1,2], Giulia Mirabello[1,2], Yifei Xu[1,2], Joseph P. Patterson[1,2], Heiner Friedrich[1,2] and Nico Sommerdijk[1,2]; [1]Laboratory of Materials and Interface Chemistry, Eindhoven University of Technology, Eindhoven, Netherlands; [2]Institute for Complex Molecular Systems, Eindhoven, Netherlands.

Magnetite, $Fe_3O_4$, is a naturally occurring iron oxide. Magnetite has excellent mechanical properties, as well as magnetic properties. Its magnetic properties depend on crystal size and shape. In nature, the formation of magnetite is precisely regulated, as controlled size and shape crystals are specifically tuned depending on the biological function, even at ambient and aqueous conditions.

Inspiration for this work was found in nature, where specialized vesicles with associated transmembrane proteins are directing nucleation and growth of the magnetite crystals. Achieving a similar level of control over crystal shape and size thus far has been challenging in synthetic procedures and the processes behind templated magnetite mineralization are still poorly understood.

Little work has been done on templated magnetite formation so far. In a bio-inspired approach, we are investigating templated magnetite growth, to precisely tune the size and shape of the magnetite crystal into a certain shape. The targeted crystal shape in this project is 2D platelets. 2D platelets of magnetite might have appealing magnetic properties, such as magnetic vortices, which result in in-plane magnetization.

A suitable template to direct magnetite growth into 2D crystals is collagen. Collagen is known to template the formation of calcium phosphate into 2D platelets, but also lepidocrocite (γ-FeOOH) (Xu *et al*., *in preparation*, **2018**). By growing magnetite into a collagen template, we are creating a novel collagen-based hybrid material with excellent mechanical and magnetic properties. To the best of our knowledge, we are the first to explore the possibilities of growing magnetite in a collagen template.

To template magnetite inside a collagen matrix, magnetite formation outside the collagen template should be inhibited. Acidic (bio-)molecules, like polypeptides, are shown to influence magnetite crystal growth. As such, those polypeptides are used to assist in mineral formation inside the template, similar to what has been exploited for calcium phosphate mineralization in a collagen matrix before.

Combining spectroscopic techniques such as Raman spectroscopy with advanced electron microscopy techniques might provide us with new insights in the mechanisms behind magnetite formation inside the template. CryoTEM already has been shown to be of great value when addressing mineral formation mechanisms. Liquid phase electron microscopy (LP-EM) allows to visualize the processes in-situ and therefore is an appealing complementary technique to CryoTEM. Preliminary experiments in the confined space of the liquid cell that is used for LP-EM measurements show that magnetite indeed has formed inside the liquid cell. After optimization of the experimental conditions, LP-EM allows for *in-situ* visualization of templated magnetite formation.

**9:30 AM BREAK**

**10:00 AM *BM09.06.06**
**Crystallization in Confinement—A Bio-Inspired Approach** Clara Anduix-Canto[1], Yun-Wei Wang[1], Yi-Yeoun Kim[1], Shunbo Li[2], Hugo K. Christenson[3] and Fiona C. Meldrum[1]; [1]School of Chemistry, University of Leeds, Leeds, United Kingdom; [2]School of Optoelectronic Engineering, Chongqing University, Chongqing, China; [3]School of Physics and Astronomy, University of Leeds, Leeds, United Kingdom.

The organisation and function of biological systems is based on compartmentalisation. Biomineralisation processes, which lead to the generation of mineral-based structures such as bones, teeth and seashells are no exception to this. Biominerals form within the confines of “privileged environments” delineated from the organism, where spatial constraints and chemical conditions can be precisely controlled. Despite this, the influence of confinement on crystallisation processes is poorly understood. This talk describes a series of systematic investigations into the effects of confinement on the formation of a range of important crystal systems including calcium carbonate, calcium sulfate and calcium phosphate. Rods of controlled pore glasses (CPGs) with

sponge-like structures were used to access true nanoscale confinement. X-ray absorption and diffraction tomography were used to study the precipitation of a population of calcium sulfate particles within these environments and we show that bassanite ($CaSO_4.0.5H_2O$) – whose existence as a precursor to gypsum ($CaSO_4.2H_2O$) has been disputed – is stable in the CPGs for periods of at least three weeks. We can also monitor the transformation from bassanite to gypsum and investigate how this leads to fracture of these porous media. At larger length scales, microfluidic devices including a novel "crystal hotel" that comprises a series of "rooms", are used to grow larger crystals. These offer many features including flow, confinement and the possibility of changing reaction conditions with time that are common to biological systems. These devices were used to image the development of crystals within confined volumes and to study the effects of soluble additives on calcium carbonate precipitation at early times. Our results show that the additives have no effect on crystal morphologies until the crystals reach at least 100 nm in size. Finally, the cylindrical pores of track-etched membranes were used to study the effects of confinement on calcium carbonate and calcium phosphate precipitation. We show that the polymorph of $CaCO_3$ changes from calcite to aragonite as the pore diameter decreases, and that aragonite is the major polymorph in 200 nm pores when low concentrations of magnesium and sulfate ions are also present. Finally, calcium phosphate precipitation in this system generates highly oriented single crystal of hydroxyapatite in small pores, where the degree of orientation is comparable to that seen in bone. Confinement therefore enables effective control over crystallisation processes, and as such promises the ability to optimise the synthesis of crystalline materials.

**10:30 AM *BM09.06.07**
**The Invertebrate Calcium Carbonate Biomineralization Process is Guided by Protein Hydrogels** John S. Evans; Craniofacial and Skeletal Biology, New York University, New York, New York, United States.

In the development of the invertebrate calcium carbonate skeletal elements, protein families are involved in the coordination of mineralization events. In many instances this process begins with the formation of amorphous calcium carbonate mineral nanoparticles which are assembled into mesoscale crystals (calcite, aragonite, vaterite) and this assembly process creates many mechanistic features of these crystals that are important for material integrity. We have observed that in the mollusk shell and sea urchin spicules that this mineralization process is guided by the formation of matrix protein hydrogel phases that stabilize, assemble, and organize mineral nanoparticles, create nanotextured crystal surfaces, and form intracrystalline nanoinclusions within the mineral phase that introduce elastic deformability to the mineral phase. These protein hydrogels form in response to protein-protein interactions that are entropically driven by intrinsically disordered and modified globular protein domain sequences, as well as protein-carbohydrate interactions involving glycoproteins. We hope that materials science will develop similar principles to create the next generation of composite materials under ambient conditions.

**11:00 AM BM09.06.08**
**Coding Cell Micropatterns through Peptide Inkjet Printing for Arbitrary Biomineralized Architectures** Wenyi Li[1], Jin Guo[1], Shengjie Ling[2], Ying Chen[1], Chunmei Li[1], Fiorenzo G. Omenetto[1] and David Kaplan[1]; [1]Tufts University, Medford, Massachusetts, United States; [2]ShanghaiTech University, Shanghai, China.

Well-designed micropatterns present in native tissues and organs involve changes in extracellular matrix compositions, cell types and mechanical properties to reflect complex biological functions. However, mimicking these micropatterns *in vitro* remains a challenge and the patterning strategies often showed limited guidance of cell orientation in relatively short culture periods. Silica-based micropatterns are popular in many biomedical fields including *in vitro* tissue models, due to the biocompatibility and high versatility of silica. Yet, harsh conditions (e.g. extremely high temperature and/or pressures) are often required to create silica patterns, and bonding between substrates is not strong enough. In this work, a *de novo* design strategy to code functional micropatterns to engineer cell alignment through the integration of aqueous-peptide inkjet printing and site-specific biomineralization is presented. Inkjet printing provides direct writing of macroscopic biosilica selective peptide-R5 patterns, which allow site-specific growth of silica nanoparticles through *in situ* biomineralization, with micrometer-scale resolution on the surface of a biopolymer (silk) hydrogel to achieve the alignment of human mesenchymal stem cell (hMSCs) and enhanced immobilization of bovine serum albumin (BSA).
To create the micropatterns, peptide-R5 was inkjet printed on the surface of enzymatically crosslinked silk hydrogels, followed by subsequent silicification to induce biosilica deposition. Linewidth and gap distance between each printed line were manipulated by adjusting drop spacing and drop volume during printing. Biomineralization was confirmed by examining silica nanoparticles covering the printed lines but not elsewhere. A 20 µm pattern gap distance and 1 µm linewidth were achieved. Well-defined peptide patterns on the substrate were also evidenced by printing fluorescein isothiocyanate (FITC)-labeled R5 and observed by fluorescence microscopy. hMSCs were cultured on the micropatterned hydrogels and specific alignment along the printed lines was noted, while the response on the unpatterned controls was randomized. Additionally, FTIC-labeled BSA and R5 were printed together and after 6 days of incubation in phosphate buffered solutions (PBS), BSA immobilized and aligned exclusively along the biosilica micropatterns, while the FITC-BSA alone extended over the surface, which suggests improved protein stability and alignment on micropatterns.
A *de novo* strategy to design functional micropatterns to engineer cell alignment and protein immobilization through inkjet printing and site-specific biomineralization was demonstrated. This cost-effective micropattern design scheme can meet a wide range of needs in the biomedical field with implications for broader material designs.

**11:15 AM BM09.06.09**
**Bio-Inspired Approaches to Creating Functional Nanocomposite Crystals** Yi-Yeoun Kim, Alex Kulak and Fiona C. Meldrum; School of Chemistry, University of Leeds, Leeds, United Kingdom.

The production of crystalline materials with structures and properties resembling those of biominerals is a challenging synthetic goal. Biominerals are invariably composite materials in which organic matrices are associated with the inorganic phase, even single crystal biominerals contain proteins embedded within the crystal lattice. Biominerals therefore provide a unique inspiration for the design and synthesis of new materials.
This talk explores how this biogenic strategy can be used to generate synthetic crystals with novel composite structures and properties and to determine the "design rules" which govern the occlusion of additives within crystals. Using polymer particles rather than proteins as simple crystal growth additives, High levels of particle occlusion is achieved by tuning the particle surface chemistry and the crystal growth conditions within calcite single crystals. Our strategy is extended to generate nanocomposites in which inorganic nanoparticles are distributed throughout a crystal matrix with true nano-scale mixing. Highly effective incorporation of gold and magnetite nanoparticles was achieved within host carbonate- and sulfate- minerals by controlling the nanoparticle surface chemistry using a physically-adsorbed double hydrophilic diblock copolymers. This methodology can potentially be applied to a huge number of nanoparticle/ host crystal systems, where its experimental simplicity makes it an attractive and general method for generating composite materials.

**11:30 AM *BM09.06.10**
**Exploring the Abiotic-Biotic Interface—From Fundamentals to Biomimetic Composites** Carole C. Perry; Nottingham Trent Univ, Nottingham, United Kingdom.

Events occurring at the solid/aqueous interface (i.e. molecular recognition, adsorption, desorption etc.) underpin a variety of technologies used in the

biomedical and biotechnological fields. The use of nanoparticles and multifunctional nanoparticles that combine recognition and targeting with specific properties is widespread for the development of clinical diagnostic tools or therapeutic platforms. Although we are developing understanding of how materials are made in nature there is a long way to go in applying that knowledge in a systematic and predictive fashion to develop new composite materials.
This presentation will highlight (a) aspects of our recent exploration of the effect of surface chemistry on peptide material interactions using both simulation (DFT) and experiment, and (b) show how we can apply this understanding to the development of novel biomimetic composites based on Pt/Au and MOFs.
In all our studies we use a wide range of experimental techniques to characterise our (bio) materials and measure their behaviour at interfaces. The research presented will include new methods being developed specifically to probe such interactions.

SESSION BM09.07: Biomimetic Crystallization
Session Chairs: Chun-Long Chen and Nico Sommerdijk
Wednesday Afternoon, November 28, 2018
Sheraton, 2nd Floor, Back Bay A

**1:30 PM *BM09.07.01**
**Creation of Hierarchical Material Structures Using Molecular Specificity** Yu Huang; University of California, Los Angeles, Los Angeles, California, United States.

Material formation in nature is precisely controlled in all aspects from crystal nucleation, growth to assembly to deliver superior functions. Specific biomolecule-material interactions have been hypothesized to play important roles in these processes. Proteins, polymers and small molecules have been extensively explored to replicate the degree of control in material formation in vitro and for nonbiogenic materials. However the organic-inorganic interfacial interaction is still far from being understood which hinders the further advancement of biomimetic material formation. In this talk I will share our efforts on decoding the myth of biomolecular specificity to material surface and their roles in controlling crystal nucleation and growth. The selection of facet specific short peptides and their abilities in guiding predictable morphology control of Pt nanocrystals will be first demonstrated. Then detailed experimental and theoretical studies on binding mechanism will be discussed. These studies open up opportunities in understanding the molecular details of inorganic-organic interface interaction, which can one day lead to the development of a library of molecular functions for biomimetic materials design and engineering.

**2:00 PM *BM09.07.02**
**Leveraging Molecular-Level Control of Peptide Constructs to Direct the Synthesis, Structure and Properties of Chiral Nanoparticle Superstructures** Nathaniel Rosi; University of Pittsburgh, Pittsburgh, Pennsylvania, United States.

Replacing one atom or linkage in an organic molecule or polymer can dramatically affect its structure and properties. Chemists have leveraged the power of synthesis to adjust and fine tune the properties of molecules. Nanoparticles are a class of fundamental structural and functional building blocks for the construction of new materials. The properties of these materials depend intrinsically on the size, shape, and composition of the constituent nanoparticles as well as the precise organization of the nanoparticles within the material. In order to fine tune the properties of the material, we must be able to carefully adjust the organization of its component nanoparticles. Can we use the power of synthetic chemistry to program and carefully adjust the structure and properties of hierarchical nanoparticle-based materials? This talk deals with peptide-based methods for controlling the synthesis and assembly of nanoparticles into well-defined chiral helical architectures. Rigorous molecular models of peptide assemblies will be detailed. It will be demonstrated that the atomic make-up of the peptide constructs can be carefully adjusted and that these subtle yet purposeful modifications lead to non-trivial structural changes to the chiral nanoparticle superstructure assembly and properties.

**2:30 PM BREAK**

**3:30 PM *BM09.07.03**
**Engineering Biology for Design and Assembly of Functional Materials** Rajesh Naik, Joseph Slocik, Kristi Singh, Maneesh K. Gupta, Kuang Zhifeng and Patrick B. Dennis; Air Force Research Laboratory, Dayton, Ohio, United States.

Biological systems offers inspiration and exciting opportunities for creating biomimetic materials, structures and devices. The assembly of individual biomolecular units into well-defined, higher-order functional structures is a hallmark of biological systems, and is exemplified in the self-organization of biological building blocks into supramolecular structures (e.g. peptides, proteins, nucleic acids, viruses). Such biological materials/systems offer inspiration and exciting opportunities for creating biomimetic materials, emulating processes and inspiring the design of devices. Furthermore, the ability to use synthetic biology tools to manipulate the genetic information encoding for biomolecules of interest allows one to design materials with tailored functionalities and properties. I will describe in my talk our research on engineering biology to create designer biomolecules or enabling the assembly of functional materials for various applications.

**4:00 PM BM09.07.04**
**Investigations into the Mechanism of Biosilicification Under *In Vitro* Conditions** Sai Maddala[1], Ernst van Eck[2], Paul H. Bomans[1], Heiner Friedrich[1] and Nico Sommerdijk[1]; [1]TU Eindhoven, Eindhoven, Netherlands; [2]Radboud University, Nijmegen, Netherlands.

Diatom biosilicas possess intricate organization, whilst requiring only ambient synthesis conditions. Their remarkable morphological properties have been a source of intense interest for chemists and biologists. Understanding the mechanisms involved in the morphological control of biosilica could inspire the production of new functional materials.
Here, we present results from our *in vitro* investigations into biomineralization of silica. Our investigations focus on mimicking the conditions present in the silica deposition vesicle of the diatoms; high silicic acid concentration (0.10 to 0.34 M), salinity, the presence of polyamines and mildly acidic pH (pH 5.5). Understanding the silica formation in these conditions is key to unravelling the mechanism of silica biomineralization.
Tetramethyl orthosilicate (TMOS) was used as silica precursor, as it readily hydrolyses to give metastable silicic acid solutions. pH was maintained at 5.5 using an autotitrator. Silicic acid consumption was monitored using ammonium molybdate assay. In the absence of polyamine additives, and under high salt conditions (NaCl concentration 0.45 M) free silicic acid was consumed in two stages, first a portion of it undergoes rapid condensation within 5 minutes, and the remainder stays unreacted for the next 27 minutes, followed by complete reduction in concentration by 43 minutes. Previous

investigations into silica formation were generally performed in pure water, and this two-stage silicic acid consumption process was not observed. The role of polyamines on silica particle formation was monitored under real-time conditions using Dynamic Light Scattering (DLS). We used polyallylamine hydrochloride (PAH, Mw 15000 g/mol) as polyamine mimic. In the absence of PAH, silica particles were observed as soon as TMOS completely hydrolysed in water. In the presence of PAH, the particle formation wasn't observed for the first 76 minutes, suggesting that the polyamines could potentially inhibit silica formation. Argon sorption porosimetry of silica gels obtained in the absence of PAH had a surface area of 170 $m^2/g$ and a pore size of 7.05 nm. Whereas in the presence of PAH, the surface area was 230 $m^2/g$ and pore size of 3.36 nm. Further analysis was performed using Cryo-TEM and solid state $^{29}Si$ NMR.
Our results indicate that under the conditions found in silica deposition vesicle of diatoms, silicic acid undergoes rapid condensation and that the presence of polyamines retard this process. This suggests that the polyamines could crucially help stabilize and store silicic acid. While the exact mechanism will be the subject of future research, our results help explain an important intermediate step in silica biomineralization.

**4:15 PM BM09.07.05**
**Building Biomimetic Bone at Higher Level of Organization** Elora Bessot[1, 2], Clement Sanchez[5], Marco Faustini[1, 2] and Nadine Nassif[3, 1, 4]; [1]UMR 7574 - Laboratoire de Chimie de la Matière Condensée de Paris, Paris, France; [2]Sorbonne Université, Paris, France; [3]CNRS, Paris, France; [4]ESPCI, Paris, France; [5]Collège de France, Paris, France.

Bone is a composite material which closely associates a dense and organized collagen organic matrix (mainly type I collagen fibrils) with an apatite mineral network. From nanometers to millimeters and beyond, bone is hierarchically structured to provide maximum strength with a minimum of material. The structure/function relationship being crucial in bone, attention needs to be paid to the long-range collagen/hydroxyapatite (HA) structure in models set *in vitro*. Recently, the cholesteric geometry was reproduced in the laboratory (Wang and al., Nat Mater 2012).

The aim of this work is to reach higher levels of bone hierarchical organizations enlarging the relevance and applications of bone models. We are working on two different organizations : the trabecular and the cylindrical motif (osteons) of the cortical bone. Both imply the texturization of the liquid-crystalline phase made of a mixture of highly concentrated acidic collagen with the HA precursors. For this purpose, different physical constraints are applied to collagen liquid-crystal phases to control the spatial arrangement of the oriented domains. Thanks to the geometry, the direction of the flow or/and the confinement, the shear forces involved may have an effect on the resulting organization.

The resulting hybrid biomimetic materials and their hierarchical organization require various characterization techniques (*e.g. in-situ* observations by polarized optical microscopy (birefringence) and investigation by SAXS/WAXS of the directed co-assembly of the organic/inorganic phases, electronic microscopies, mechanical tests *etc*).

By using an original strategy, we aim to improve our knowledge on processes involved in the bone tissue (morphogenesis) as well as build new biomimetic hierarchically-structured materials that offers remarkable scaffolds to repair larger defects for bone tissue engineering.

**4:30 PM *BM09.07.06**
**Harnessing the Precision of Biorecognition for the Development and Assembly of Responsive, Functional Inorganic Nanomaterials** Marc R. Knecht; Univ of Miami, Coral Gables, Florida, United States.

Nature has exploited the precision of biorecognition events for the development inorganic materials for critical applications ranging from protection against predation to structural support. These materials are generated under sustainable conditions where the translation of such approaches to material compositions of technological importance could provide pathways to address current needs in applications ranging from energy harvesting and storage to biological sensors and theranostic systems. At present, only minimal understanding is known concerning the direct interaction between biological and bio-inspired molecules (e.g. peptides, DNA, peptoids etc.) with inorganic materials, where the ability to predictably design these biomolecules with affinity for the target system remains unachieved. By having such capabilities, the ability to fabricate functional materials with desired properties on demand could be accessed for immediate use in targeted applications. In addition, due to the great complexity achievable from biosystems, the biomolecules could be designed with secondary functionalities beyond inorganic material affinity, thus generating final structures with multifunctional capabilities. Our research has focused on the design of new bio-inspired systems with the ability to fabricate functional inorganic materials and drive their assembly in three dimensions. This assembly process is accessed based upon the multifunctional capability of the peptides to recognize and bind the inorganic surface, while simultaneously self-organizing in three dimensional space. In one instance, the self-assembly process is driven through biomolecule-biomolecule interactions, while in a second case, the assembly process is achieved through crosslinking of multiple inorganic materials from a single biomolecule. This research demonstrates multiple, disparate pathways from which biorecognition events can been exploited to drive inorganic material assembly, which could be tailored to different systems based upon biomolecular affinity.

SESSION BM09.08: Poster Session II: Bioinspired Materials
Session Chairs: Chun-Long Chen and Nico Sommerdijk
Wednesday Afternoon, November 28, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

**BM09.08.01**
**Dehydration Stability Analysis of DNA-Guided Nanoparticle Superlattices** Hayato Sumi[1], Takumi Isogai[2], Shoko Kojima[1], Shunta Harada[1, 2], Toru Ujihara[1, 2] and Miho Tagawa[1, 2]; [1]Graduate School of Engineering, Nagoya University, Nagoya-shi, Japan; [2]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya-shi, Japan.

Nanometer-scale materials which have unique electric, photonic, phononic and magnetic properties are hard to control and create. The self-assembly of DNA-guided nanoparticles has attracted much attention as a novel technique to design nanostructures flexibly due to the programmability of DNA base sequences. DNA-functionalized nanoparticles (DNA-NPs) can assemble into various types of 3D nanoparticle superlattices by using sequence-selective DNA hybridizations. However, DNA-NP superlattices have a problem in structure stability. Whereas DNA-NP superlattices are stable in a buffer solution, they collapse outside the solution because of the dehydration of DNA strands. Resin- or silica-based encapsulation method is one way of solving the problem in terms of the stabilization. For a wide range of applications, the direct dehydration of DNA-NP superlattices, without any filler, is crucially

important. It has been reported that the volume fraction of nanoparticles per DNA-NP superlattice volume is relatively sensitive to the structure stability of the DNA-NP superlattice during dehydration, however the optimum condition of the volume fraction for the structure integrity has not yet been studied. Here, we investigate the optimum condition for the dehydration of DNA-NP superlattices by controlling the volume fraction of nanoparticles per unit cell in solution by using different sized nanoparticles.
Firstly, Au nanoparticles were functionalized with thiolated-DNA strands. These DNA-functionalized nanoparticles were combined with linker DNA strands, which hybridize to complementary sequences. Secondly, the mixture solution was heated up to 65 ºC and then slowly cooled back to 25 ºC. By changing the combination of DNA base sequences and nanoparticle sizes, we designed 3D superlattices to be assembled into bcc, fcc and CsCl structure, respectively. The crystal structures of DNA-NP superlattices were analyzed by small angle X-ray scattering (SAXS) before and after dehydrations. The shapes and the surface structures of dehydrated samples were observed by scanning electron microscopy (SEM).
By analyzing SAXS patterns, the assemblies of DNA-NPs in solution were identified as bcc, fcc and CsCl superlattices as we designed. We also tried to analyze the assemblies of DNA-NPs after dehydration and for the first time we have succeeded in highly accurate structure analysis of direct dehydrated DNA-NP superlattices with higher volume fractions of nanoparticles per unit cell, which exhibited clear diffraction patterns. It has also been confirmed that direct dehydrated DNA-NP superlattices with higher volume fractions tended to maintain their lattice symmetries regardless of crystal structures. SEM analysis confirmed DNA-NP superlattices with faceted crystal shapes and ordered arrangements of Au nanoparticles on their crystal faces at higher volume fractions, which also indicates the structurally stable dehydration process while retaining their lattice symmetries.

**BM09.08.02**
**A New Hydrogel Based on Aldehyde-Terminal Peptide for Amine Drugs Controlling Delivery** Youzhi Wang; State Key Laboratory of Medicinal Chemical Biology, Nankai University, Tianjin, China.

Supramolecular hydrogels hold great promise for controlled drug delivery. We reported on a supramolecular hydrogel based on an aldehyde-terminal peptide. The hydrogel was prepared *via* the enzyme instructed self-assembly (EISA) process.
The hydrogelator could form Schiff base with amine drugs. The resulting hydrogels showed an ultra-stable property in highly acidic or basic aqueous solutions. Due to the pH-responsive property of Schiff base, the hydrogels could be applied for controlled release of encapsulated amine drugs (doxorubicin).
As a result, doxorubicin released faster at acidic pH values (5.5, 6.5) than neutral pH value (7.4) in the hydrogels (The 24 hours accumulative released percentage of Dox at pH 5.5, 6.5 and 7.4 was 15.38, 13.45 and 10.98%, respectively.). Tumor microenvironment was reported having acidic pH values from pH 5.8 to pH 7.6. We think our strategy provides a novel peptide-based hydrogel that may be applied in controlling delivery of amine containing therapeutics.

**BM09.08.03**
**Catalyzed Organic Reactions in Aqueous Media Using Hierarchically-Structured Nanomaterials Assembled from Sequence-Defined Peptoids** Tengyue Jian and Chun-Long Chen; Pacific Northwest National Laboratory, Richland, Washington, United States.

Natural enzymes are highly efficient and selective catalysts that present unique catalytic microenvironments. Development of highly stable enzyme- mimic catalysts using sequence-defined synthetic molecules will benefit the area of biomimetic catalysis and facilitate our understanding of the structure-depended catalytic performance. Here we report the design and synthesis of peptoid-based biomimetic materials with hierarchical structures for catalyzing the direct asymmetric aldol reaction and hydrolysis reaction in aqueous media. First we synthesized and assembled 20 proline-containing membrane catalysts, and demonstrated their catalysis of asymmetric aldol reaction with high conversion yields and good enantio- and diastereoselectivities. We further showed that both the enantio- and diastereo-selectivities of this aldol reaction are highly dependent on the hydrophobic microenvironment built around catalytic sites. For the hydrolysis reaction, we found that imidazole and pyridine-containing 2D membranes catalyzed this reaction in aqueous media with high efficiency. We demonstrated the use of peptoid nanomembranes for degradation of nerve agent simulants: 4-nitrophenyl phosphate and acyl ester (nitrophenylacetate and pyrene ester). In this catalyzed hydrolysis reaction, we found that the addition of $Zn^{2+}$ and $Cu^{2+}$ significantly accelerated the hydrolysis rate. We further demonstrated that these catalyzed organic reactions are highly dependent on the morphology and crystallinity of peptoid assemblies.

**BM09.08.04**
**Ultrastable Supramolecular Hydrogel of Hydrophobic Peptides Prepared by a Hydrolysis Process** Guojuan Pu; State Key Laboratory of Medicinal Chemical Biology, Nankai University, Tianjin, China.

Supramolecular hydrogel based on peptides self-assembly have attracted extensive research interests in recent years, but its application in the field of nanomedicine is still limited by its poor stability in extreme environments. The number of hydrophobic amino acids directly affects the solubility of the peptides and the properties of the hydrogel. Peptides FF (F: Phenylalanine) has strong assembly capability, those hydrogels based on dipeptide of FF are the most widely investigated. Organic solvent is always required to dissolve peptides because of its strong hydrophobic properties. However, there is no hydrogel containing more than three Phenylalanine currently in aqueous solution.
TTherefore, we describes a method for the preparation of hydrogels containing hydrophobic FFFF and FFFFF sequences by ester bond hydrolysis, which resulted in two highly potent peptide hydrogels formed by Nap-GFFFFF-GP-EE and Nap-GFFFF-GP-EE (GP: Glycolic Acid). Then the transparent hydrogels were formed at 37 degrees Celsius for about 48h. The hydrogel had excellent stability in highly acidic (pH=1) and highly basic solutions (pH=13) for 15 days.
In conclusion, a novel method was constructed to promote hydrophobic peptides to dissolve in water and form a supramolecular hydrogel by the ester and the bond hydrolysis method, even if the molecule itself is unable to form a hydrogel and there is low solubility with ultrasound or heat means. This approach should be applicable for exploring supramolecular assemblies formed by other hydrophobic peptides. From the above, useful information for hydrogels of hydrophobic peptides has been presented through our study.

**BM09.08.05**
**Organic-Inorganic Bio-Hybrid Nanoparticle for Systemic Cellular Delivery of Superoxide Dismutase to Prevent Acetaminophen-Induced Hepatotoxicity and Liver Injury** Min Sang Lee and Ji Hoon Jeong; Sungkyunkwan University, Suwon-si, Korea (the Republic of).

Direct delivery of proteins into cells has been considered an effective approach for treating the protein-related diseases. However, clinical use of proteins has still been limited due to their instability in the blood and poor membrane permeability. To achieve an efficient cellular delivery of the protein to target cells *via* a systemic administration, a multifunctional carrier system having desirable stability both in the blood stream and the cells, specific cell-targeting property and endosomal escape functions may be required.
In this study, we designed organic-inorganic bio-hybrid nanoparticle containing an active enzyme by cross-tethering multiple superoxide dismutase (SOD)

molecules with 3,4-dihydroxyphenylalanine (L-dopa)-derivatized hyaluronic acid (d-HA). SOD was conjugated with d-HA by reacting surface amines of SOD with catechol moiety of d-HA through Michael-type addition and Schiff base formation, which forms a hydrophilic network mesh pouch containing multiple SOD molecules tethered with HA chain networks. The free catechol groups that were not involved in the conjugation chelated calcium ions, resulting in formation of ultra-small calcium phosphate nanoparticles (USCaP, 2-5 nm) decorated on the surface of the nanoparticle. The permeable shell of hydrophilic HA chains effectively protects the enzyme from degradation in the blood after intravenous administration and provides an additional function for targeting hepatocytes expressing HA receptor (CD44). The structure and catalytic activity of the enzyme molecules in the nanoparticle were not significantly compromised in the nanoparticle. In addition, dissolution of USCaP in acidic environment efficiently improved the endosomal escape after cellular uptake, resulting in the rapid release of d-HA/SOD into the cytoplasm. The SOD-containing nanoparticle fortified with USCaP was used for the treatment of acetaminophen (APAP)-induced fulminant hepatotoxicity and liver injury. The systemically administrated nanoparticle achieved the efficient hepatic cellular delivery of SOD and resulted in efficient removal of reactive oxygen species (ROS) in the liver and remarkable improvement of APAP-induced hepatotoxicity and liver injury in animals.

**BM09.08.06**
**Fine-Tuning Core-Shell Nanoparticle Growth by Exploiting Ions Doping** Jianxiong Zhao, Xian Chen, Bing Chen and Feng Wang; Materials Science and Engineering, City University of Hong Kong, Hong Kong, Hong Kong.

Predicting and tailoring the morphology of core shell nanoparticle is indispensable in obtaining desirable properties for optical and biological applications. However, the incomplete and discontinuous shell growth induced by heterogeneity in structure and chemical bonding may reduce the luminescence intensity and detriment to particle uniformity. Here, we demonstrate a strategy of ions doping for forming continuum $NaREF_4$ (RE= rare earth) shell growth on heterogeneous core.

Compared to those un-doped shell which formed homogeneous nucleation surround the core. We show that doping can greatly reduce the energy barrier of heteronucleation, making shell successfully deposit on core. The core shell structure are distinguished by using high-angle annular dark-field scanning transmission electron microscopy. The shell growth process at different reaction stages are revealed by transmission electron microscopy observation on nanoparticle extracted during the reaction. We show that nascent shell layer formed at low energy crystallographic facets, afterward, shell extended and merged together over entire core surface.

We applied the strategy on core particle with different size and dimensions. All shell growth is stabilized but with some morphology variation for different core shape. The TEM analysis show that shell growth is not only strongly dependent on the nature of the different facet, but also reliant on mechanical flexibility of core. Moreover, the strategy improves both upconversion emission and lifetime of core shell nanoparticle and simultaneously provide novel platforms for building multifunctional self assembled composites.

**BM09.08.07**
**Liquid Crystalline Disubstituted Polyacetylene-Preparation, Properties and Possible Applications for Biomimetic Materials** Kyoka Komaba[2], Masashi Otaki[1] and Hiromasa Goto[1]; [2]University of Tsukuba, Tsukuba, Japan.

Many polymers mimicking ecosystem such as DNA have been synthesized. Synthesis of helical macromolecules has been inspired by such natural polymers. In this report, we synthesized disubstituted polyacetylenes using tantalum based catalyst. Chemical structure and optical properties of the polymer thus synthesized in this study are characterized with infrared absorption spectroscopy (IR), gel permeation chromatography(GPC), UV-vis absorption (UV) spectroscopy, circular dichroism (CD), fluorescence spectroscopy, and polarized optical microscopy analyses. Polyacetylene as a conductive polymer has some drawbacks such as poor stability in the air, no solubility, low processability. Introduction of substituent to the polyene backbone allows improvement of its disadvantages. Introduction of liquid crystal group can improve such drawbacks. We synthesized liquid crystal polyacetylenes for potential applications in biological field.
We succeeded in synthesis of disubstituted polyacetylene using tantalum chloride catalyst (Y = 41%). GPC result indicated that number average molecular weight ($M_n$) of the polymer is to be > 1,000,000 and degree of dispersion ($M_w/M_n$) ca.1.4.
The IR spectroscopy measurements confirmed that polyene was successfully produced by opening of the C≡C bond of the monomer in the polymerization. Polymer shows two absorption maxima at around 370 nm and 430 nm in the UV-vis. These absorption bands are derived from p-p* transition of the main chain. The polymer shows no CD signals. This result indicates that the polyacetylene derivative synthesized in this report contains equimolar amount of right-handed and left-handed helical structures, resulting in racemic state. This polymer shows fluorescence signal at around wavelength 500 nm.
Polarizing optical microscopy observations for the drop cast film from toluene solution deposited on a glass substrate was carried out. This polymer shows fan-shaped texture of smectic liquid crystal with lyotropic liquid crystallinity. The layer structure has similarity to biological membrane. This unique structure may be artificial lipid bilayer membrane.
In this work, we achieved synthesis of disubstituted polyacetylenes with large molecular weights, showing lyotropic liquid crystallinity with layer structure. We evaluated that the simple synthesis of liquid crystal poltyacetylene derivatives having no mesogenic group from readily available monomers affords to production of the biomimetic lipid bilayer membrane.

**BM09.08.08**
**Selenium- and Tellurium-Containing Block Copolymer with Multi-Hierarchical Oxidation Response** Lu Wang and Huaping Xu; Department of Chemistry, Tsinghua University, Beijing, China.

Nanomaterials with hierarchical responsiveness are of great significance for not only fundamental science but also future biomedical applications due to sophisticated and hierarchical physiological environments. Here, we report a selenium- and tellurium-containing block copolymer that can be stepwise oxidized by both chemical methods and electrochemical methods. Differences in sensitivity to the oxidation of selenium and tellurium were employed. By tuning the concentration of the oxidant and oxidation periods, self-assembly behaviors of the copolymer were tuned by stepwise chemical oxidation. After oxidation, some interesting morphological evolution was observed that the polymer micelles crosslinked with each other without any swelling. In the case of electrochemical oxidation, the voltage during the electrochemical oxidation and oxidation period also affected the level of oxidation. Furthermore, we showed that the degree of electrochemical oxidation varied with a different PEG block length. Considering sophisticated physiological conditions in vivo, this hierarchically responsive system may provide new possibilities as smart delivery vehicles in biological environments.

**BM09.08.09**
**Sequence-Designed pH-Responsive Pure DNA Hydrogel Produced by Rolling Circle Amplification** Guoyuan Liu[1], Leilei Tian[1], Yishun Huang[1], Wanlin Xu[1, 2], Haoran Zhao[1], Pan Li[1] and Jing Li[1]; [1]Material Science and Engineering, Southern University of Science and Technology, Shenzhen, China; [2]Zhengzhou University, Zhengzhou, China.

Stimuli-responsive DNA hydrogels, albeit the potential advantages like biocompatibility and ease to functionalize, problems remain in the reconciliation

between facile fabrication and stimuli-responsiveness. In this study, by rationally designing the sequence of DNA chains, pH-responsive sites-namely, i-motif forming sequences (IFSs)- were introduced during rolling circle amplification. At pH 5.0, the resultant gelation occurs driven by the formation of intermolecular i-motifs as crosslinkers.

To better evaluate the sequence influence on the responsiveness, three IFSs were designed and named as $I_1$, $I_2$, and $I_3$ whose sequences are CCCCCTCCCCC, CCCTCCCTCCCT, and CCCAATCCCAATCCCAATCCC. Three IFSs form primarily inter-molecule, both inter-and intra-molecule and primarily intra-molecule i-motif structure respectively. The difference in sequence reflects on the pH-responsiveness during sol-gel transition. When adjusting the pH from 5.0 to 8.0, $I_3$ quickly dissolved while $I_1$ became softer but remain intact and $I_2$ became more dispersed in the buffer. We draw a conclusion that the gelation process can be tuned via sequence design. An IFS favoring intramolecular i-motif leads to mechanically weak, thermally unstable yet pH-sensitive hydrogel while for IFS favoring intermolecular i-motif structure, gelation may occur along with quick condensation which promotes non-specific interactions within the gel.

The microstructure of the hydrogel was investigated to dig some evidence of the gelation mechanisms. RCA products at neutral (pH 7.5) and acidic condition (pH 5.0) were observed under scanning electron microscope. Of all three samples, flower-like microstructures (FMs) with diameter of 2-3 μm was observed in a large amount. FMs were believed to be a *in situ*formed by-product of DNA polymerization and performs a crucial role in gelation process. Form the SEM images, the hydrogel morphology featured with thick DNA matrix embedded with FMs. For sol, the FMs is more visible due to the lack of matrix surrounding. Also, the different properties of specimen can be explained. For $I_1$, dense matrix already formed in neutral pH indicating many crosslinking sites that are not i-motif structures. For $I_3$ the matrix in acidic buffer is relatively looser which is consistent with the weak stability. Worth noting that there is no RCA matrix in $I_2$ after redissolved in pH 8.0 buffer yet the FMs remain unchanged. This proves that FM, as a condensed complex of DNA and magnesium pyrophosphate (MgPPi), has no pH-responsiveness and that the pH-adjusting gelation exclusively relies on introduced i-motif sequences.

To summarize, this work proposed a facile method to produce pH-responsive DNA hydrogel. Also, the influence of three different IFS sequences on gelation mechanism as well as their interaction with flower-like microstructures were investigated.

**BM09.08.10**
**Hybrid Thin-Film Formation of Zinc Layered Hydroxides with Intercalated Organic Molecules Through a Biomineralization-Inspired Approach** Satoshi Kajiyama, Takashi Kato and Fumiya Katase; Univ of Tokyo, Tokyo, Japan.

Biomineralization-inspired crystallization is one of effective approaches for the development of hierarchical structures from nano- to macro- scales under ambient conditions [1-3]. In biomineralization, acidic polymers induce amorphous states of inorganic crystals with the interaction between acidic groups and metal ions. The amorphous states are useful as precursors for inorganic crystals with ordered structures [4,5]. We have achieved the formation of hybrid thin films based on zinc hydroxide carbonate (ZHC) with ordered nanostructures through biomineralization-inspired approach utilizing amorphous precursors. ZnO thin films have been obtained with ordered structures from ZHC ordered hybrid thin films through thermal treatment [6].
In the present study, we demonstrate that hybrid thin-film formation composed of zinc layered hydroxides with intercalated organic molecules through the biomineralization-inspired approach utilizing amorphous states as precursors. The amorphous precursors for zinc layered hydroxides with intercalated organic molecules were prepared in the presence of poly(acrylic acid). Polymer thin-film matrices were immersed in aqueous solution containing the amorphous precursors in order to develop hybrid thin films. The structures of resultant hybrid thin films composed of layered zinc hydroxides have been examined with polarizing optical microscopy, scanning electron microscopy and X-ray diffraction . These characterizations revealed that the hybrid thin films of layered zinc hydroxides exhibit macroscopically ordered structures. Hybrid thin films comprising of the layered zinc hydroxides are converted to ZnO thin films through thermal treatment. The resultant ZnO thin films exhibit macroscopically ordered structures. It is elucidated that ordered structures of ZnO thin films depend on the molecule structures of intercalated guest molecules as well as the original structures of hybrid thin films of layered zinc hydroxides. These results suggest that the biomineralization-approach is useful for the development of functional ZnO materials with ordered structures.

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**BM09.08.12**
**Macromolecular Assembly of DNA into Complex Nanostructures via Hybridization Chain Reaction** Laura A. Lanier and Harry Bermudez; Univ of Massachusetts-Amherst, Amherst, Massachusetts, United States.

Through the use of a macromolecular self-assembly technique called hybridization chain reaction (HCR), we have created complex, well-defined nanostructures. HCR is a supramolecular polymerization of DNA that proceeds as an isothermal cascade of strand displacement reactions. Two DNA monomers are kinetically trapped in hairpins until the addition of an initiator strand opens the hairpin of one monomer through a strand displacement reaction. The unhybridized end then opens the hairpin of the other monomer through a strand displacement reaction. This cascade of strand displacement reactions continues, producing a supramolecular DNA polymer. This project aims to demonstrate the living mechanism of HCR. Further, the living nature of HCR is used to create well-defined nanostructures of DNA by HCR in order to expand the design toolbox of DNA for potential applications in such fields as nanomedicine, sensing, synthetic biology.

We have demonstrated that HCR produces supramolecular polymers of DNA in a controlled manner through a living polymerization mechanism. Through macromolecular assembly by HCR, DNA polymers of narrow dispersity are produced whose molecular weight is controlled by the monomer to initiator stoichiometric ratio, consistent with a living polymerization mechanism. Additionally, HCR polymerization can be continued by the addition of further monomer, demonstrating its living nature by the absence of termination and chain transfer reactions. Identification of the living character of HCR presents new opportunities in macromolecular assembly of structural DNA nanotechnology and molecular biology.

Utilizing the demonstrated living nature, complex, well-defined nanostructures are created via HCR. Bottlebrush structures are created by modifying the monomer to include an additional overhang that initiates a secondary HCR polymerization with aspect ratio controlled by the stoichiometric ratios of the initiator and monomer strands of each HCR sequence. Supramolecular star polymers are created by modifying a four-arm star to initiate HCR from each arm. The growth of each arm is independently controlled, allowing for the creation of asymmetric DNA star polymers. The creation of these complex nanostructures is demonstrated by gel electrophoresis and atomic force microscopy.

**BM09.08.13**

**Enzymatically Activated Aggregation and Cell-Adhesion of Peptide-Nanoparticle Conjugates for Surface-Enhanced Raman Spectroscopy (SERS) Based Diagnostics and Imaging** Hailin Huang[1, 2, 3], Stephen O'Brien[1, 3], Duncan Graham[4] and Rein Ulijn[2, 5, 3]; [1]The City College of New York, New York, New York, United States; [2]CUNY Advance Science Research Center, New York, New York, United States; [3]The Graduate Center, City University of New York, New York, New York, United States; [4]Applied and Pure Chemistry, University of Strathclyde, Glasgow, United Kingdom; [5]Chemistry, Hunter College, New York, New York, United States.

In cancer research, multi-functionalized gold nanoparticles (GNPs) have advanced to realize simultaneous diagnosis and therapy (i.e. theranostics) due to their excellent optical properties and accessibility of surface modification. An example of GNPs used for cancer theranostics is to functionalize the surface using Raman reporter molecules for surface enhanced Raman spectroscopy (SERS) and incorporate anti-cancer drug molecules on the surface. One critical aspect of using nanomedicines for cancer treatment is to assure that the administered drugs reach and accumulate at the tumor site, rather than retaining at healthy parts of the body or being eliminated by the reticuloendothelial system. Unfortunately, during the past 10 years, the delivery efficiency of nanoparticles has not been improved significantly, and only a median of 0.7% of injected dose of nanoparticles reached the tumor. Increasing the delivery efficiency is therefore one of the greatest challenges for the development of cancer nanomedicines.
In this study, an enzyme responsive peptide functionalized GNP is designed to target metastatic tumor cells with a new dual-action targeting mechanism. Immobilized peptides with which contain an enzyme-cleavable linker which incorporates a cryptic adhesive ligand are immobilized onto GNP and recognized and cleaved by collagenase MMP-9. MMP-9 is overexpressed by malignant tumor cells and plays a central role in metastatic cancer progression by degrading proteins in the extracellular matrix (ECM). The enzymatic product fragments retained on the surface of GNP, LRGDC, trigger nanoparticle self-assembly and enhances SERS signals. Moreover, the RGD motif binds preferentially to $\alpha_v\beta_3$ integrins which are protein receptors overexpressed on tumoral endothelial cells primarily during angiogenesis. The advantage of this design is that the surface functionalized GNPs remain an inactive state through the blood circulation and become active once they reach the tumor ECM, not only exposing the RGD surface for cell binding, but also enabling tumor diagnosis by SERS. This active targeting mechanism can potentially reduce the binding of RGD to non-tumoral integrins and hence increase the delivery efficiency of the nanoparticles.

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**BM09.08.14**

**Octopus-Inspired Adhesive and Conductive Patch Sensor for Biosignal Monitoring** SeungHoon Choi[1], HeonJoon Lee[2] and Changhyun Pang[1, 2, 3]; [1]Sungkyunkwan University Advanced Institute of NanoTechnology, Suwon, Korea (the Republic of); [2]School of Chemical Engineering, Sungkyunkwan University, Suwon, Korea (the Republic of); [3]Samsung Advanced Institute for Health Science and Technology, Suwon, Korea (the Republic of).

The attachment phenomena of various hierarchical architectures found in nature have extensively drawn attention for developing highly biocompatible adhesives for skin or wet inner organs. Scientists have reported bioinspired skin adhesives with various multiscale architectures including patches with mushroom-shaped tips with or without conductive materials, microneedles, and miniaturized octopus-like suction cups. Adhesives with mushroom-shaped tips have demonstrated enhanced attachment by van der Waals interactions on dry skin, and stabilized contact to active skin surface underwater by embedding the patch underneath swimwear. These adhesives, however, cannot maintain adequate adhesion on wet skin or skin under flowing water. Microneedle patches have indicated striking adhesion performances through mechanical interlocking, but they are more appropriate for wound closure or invasive therapies rather than reversible and residue-free dermal attachment. In recent years, hierarchical structures of octopus suckers have been investigated for their unique reversible adhesion in both dry and wet conditions. The octopus sucker can be divided into two parts: 1) the protruded cup-like upper portion (infundibulum) and 2) the lower portion with a dome-like protuberance (acetabulum). For such adhesive capabilities, suction cups of octopi have been mimicked to develop reusable and residual-free skin patches for versatile medical applications. Here, we present an octopus-inspired skin-adhesive with meniscus-controlled unfoldable 3D microsuckers in micropillars, as well as its application to a stretchable patch sensor composed of carbon-based conducting polymer composite (CPC) films. Mimicking the rim and infundibulum of octopus suction cups, the microsuckers are fabricated by controlling the wetting properties of a liquid precursor during simple molding. Moreover, the adhesive shows strong dry/wet adhesion performances in both pull-off and peeling-off directions against a wafer and rough, hairy skin. Finally, the patch sensor incorporated with 3D microsuckers displays sensitive and reliable piezoresistive responses to lateral strain and vertical pressure. With high conformity on human skin and water-resistant nature, our patch sensor demonstrates efficient detection of not only electrocardiogram (ECG), but also the motion of a human finger even in an underwater environment. We believe that this work represents a timely, methodological advance in nature and breakthrough in the fields of wearable and skin-attachable sensor devices for future healthcare applications.

**BM09.08.15**

**Antimicrobial Modification of K-Wires via Novel Polymer Grafting Technology** Mikhail A. Bredikhin[1], Dmitry Gil[2], Christopher Gross[3], Igor Luzinov[4] and Alexey Vertegel[1]; [1]Bioengineering, Clemson University, Clemson, South Carolina, United States; [2]Medical School, Harvard University, Boston, Massachusetts, United States; [3]Department of Orthopedics, Medical University of South Carolina, Charleston, South Carolina, United States; [4]Materials Science & Engineering, Clemson University, Clemson, South Carolina, United States.

**Introduction:** Kirschner wires are the external smooth stainless-steel pins that are used today in bone fracture fixation. These wires provide the surface for bacteria to adhere onto and form a biofilm, which makes them considerably less-susceptible to antibiotics. The solution to this problem has been an active area of research.
Surface coatings of implants with bioactive molecules is a modern approach to modify implant's function. However, in the case of K-wires, coating the pin with an antibiotic would not have much effect *in vivo* since this coating is poorly adherent and would be easily removed when the wire is drilled by a surgeon. In this work, we propose a novel method of grafting the K-wires with highly adherent polymer. Specifically, this study utilizes cross-linkable random "brush" copolymer of OEGMA, GMA, and LMA, which can be covalently attached to solid surfaces. Such polymeric coating can be loaded with an antibiotic, allowing both the protection of the antimicrobial coating during insertion into the bone and optimal release over time.
**Materials&Methods:** Gentamicin sulfate (GS), butanone-2 (MEK) and other materials were purchased from Sigma-Aldrich. The polymeric "brush" is synthesized via solution polymerization. Grafting of the polymer onto the surface was performed by dip-coating. The wires were dipped in the MEK solution of the polymer. Following thermal cross-linking of the polymer, the polymer-coated wires were submerged and kept in aqueous GS solution for 24

hours. Finally, the wires were washed with DI water to remove weakly-bound drug, and then air-dryed. For the negative controls, the wires were dipped in the plain MEK solution and the MEK:Chloroform solution of polylactic acid (PLA). The next steps were the same as for the poymer-coated wires. Surface of the wires was then characterized using AFM, SEM, and FT-IR.
Antmicrobial *in vitro* studies were carried out with *S. aureus*. We have tested the ability of the prepared wires to kill planktonic bacteria exposed to them and to prevent biofilm formation on the wire surface by colony forming unit (CFU) plate count method using standard FDA protocols.
Finally, coated wires were drilled into human femur model. Their antimicrobial efficacy was assessed again after this procedure.
**Results and Discussion:** While the uncoated wires showed no anti-bacterial activity, the polymer-coated wires were highly antimicrobial showing maximum inhibiting concentration of 10^5 CFUs/ml/cm of wire. The PLA-coated wires exhibited similar antimicrobial effect. However, only the polymer-coated wires retained bactericidal properties after drilling into human femur bone model. PLA layer was almost completely removed after the mechanical shear stressing by drilling, which was confirmed by FT-IR analysis of the surface. Thus, the polymer coating of K-wires provides an appropriate drug-carrying and drug-protecting system for the bone implant, where the shear stress during implantation plays a significant role.

**BM09.08.16**
**Ultra Long-Scale Silver Nanowire with Self-Templating M13 Bacteriophage** Kyounga Lim[1], JongMin Lee[1], Vasanthan Devaraj[1], Yeong Ju Lee[1] and Jin-Woo Oh[2, 1]; [1]Research Center for Energy Convergence and Technology Division, Pusan National University, Busan, Korea (the Republic of); [2]Department of Nanoenergy Engineering, Pusan National University, Busan, Korea (the Republic of).

These days, electron devices demand high performance electrode. Ag nanowire is the most promising candidate because it has excellent electrical property, however, the process of Ag nanowire synthesis is complicated and it is difficult to obtain long-scale Ag nanowires in traditional methods.
M13 bacteriophage is a helical structured biomaterial with 6.6 nm of the diameter and 880 nm of the length. M13 bacteriophage can be reproduced through self-cloning and modified the chemical properties by genetic engineering. According of these properties, M13 bacteriophage is very useful as a template. In this work, we fabricated ultra long-scale Ag nanowire using genetically engineered M13 bacteriophage. We observed that the crystallinity of Ag nanowire (length or diameter) was affected as changing the engineered chemical structure on major coat protein of M13-bacteriophage. The range of Ag nanowire was around 50 nm to 200 nm and the average length and diameter were around 100 um and 1 um, respectively. The maximum length of Ag nanowires that was observed was 300 um. The existence and morphology of Ag nanoparticles and nanowires were confirmed by FE-SEM (field emission scanning electron microscope) and high resolution TEM (transmission electron microscope). To examine the components of Ag nanoparticles and nanowires, map profiling was conducted by EDS (energy dispersive spectroscopy).

**BM09.08.17**
**High-Density Enzyme Array on Self-Assembling Protein Template for ELISA-Type Detection of Biomarkers** Gi Ahn Jung, Samuel Lim and Douglas S. Clark; University of California, Berkeley, Berkeley, California, United States.

Enzyme-linked immonosorbent assay (ELISA) provides a simple and convenient way to detect biomarkers, and is widely used as a diagnostic tool. The components of ELISA consists of a primary antibody specific to the target antigen, and a secondary antibody that binds the primary antibody to render it detectible; commonly, the secondary antibody is coupled to an enzyme that allows for a colorimetric assay. Although conventional ELISA has proven very useful in both research and clinical applications, it can suffer from poor sensitivity when the biomarker concentration is too low.

We propose a strategy to enhance the sensitivity of ELISA based on the self-assembling filamentous protein g-prefoldin (gPFD), which was isolated from the hyperthermophilic archaeon *Methanocaldococcus jannaschii*. Using the streptavidin-biotin interaction, gPFD was engineered to template horseradish peroxidase (HRP) enzymes in high density and close proximity along its filamentous backbone; subsequently, the HRP-gPFD complex was fused to the secondary antibody. Each secondary antibody is coupled to the array of HRP enzymes, with the aim of increasing the antigen sensitivity compared to conventional ELISA. The strategy demonstrated here may further improve currently used ELISA techniques, allowing for the efficient detection of biomarkers in both research and clinical settings.

**BM09.08.18**
**Study of the Behavior of an Artificial Membrane Immersed in Aqueous Medium** Marcelo A. Cisternas[1, 3], Sebastian A. Molina[1, 3], Maria J. Retamal[2, 3], Nicolas H. Moraga[1, 3], Hugo I. Zelada[1, 3], Tomas P. Corrales[4], Diego I. Diaz[1, 3], Rodrigo E. Catalan[1, 3] and Ulrich G. Volkmann[1, 3]; [1]Instituto de Física, Pontificia Universidad Catolica de Chile, Santiago, Chile; [2]Facultad de Quimica, Pontificia Universidad Catolica de Chile, Santiago, Chile; [3]CIEN-UC, Pontificia Universidad Católica de Chile, Santiago, Chile; [4]Departamento de Fisica, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile.

Self-assembly of artificial membranes on solid substrates has gained importance due to the potential applications in the field of BioNanotechnology. Artificial membranes represent models for study of the behavior of biological membranes, which are the base of the cell membrane structure. The cell membrane is composed by different kind of lipids and proteins that change their behavior when they are stimulated physically and/or chemically.

Samples were made using a silicon substrate to support the lipids that compose the membrane. First, the substrate were cleaned using the Tidswell method to remove all organic material from the surface. Second, we evaporated the DPPC [1] phospholipid that self-assembled in bilayers when hydrated. The growth of the DPPC layer on the substrate was controlled *in situ*using Very High Resolution Ellipsometry (VHRE) to obtain the specific thickness of the film.

In our previous work, we measured the capacitive response of the system composed by a phospholipid bilayer on a thin chitosan (CH) layer, both deposited onto silicon substrate [2] and immersed into a protein solution of gramicidin. The change of the capacitive response permit us to confirm the gramicidin ion channel formation across the membrane, to transform our phospholipid bilayer into an artificial membrane. Our results showed a change in the system response due to the protein insertion across the membrane, but it was necessary to perform a detailed study of the membrane immersed into an aqueous medium.

In this work, the behavior of the artificial membranes immersed into an aqueous medium was studied. This medium simulates the natural environment of the biological membrane in laboratory conditions. For this purpose, was designed and constructed an aqueous cell as an accessory of our VHRE. In this cell we immersed the substrate and applied temperature ramps to measure the phase transitions of the phospholipid bilayer.

Acknowledgments

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**BM09.08.19**
**The Differences Between Colloidal and Crystalline Evaporative Deposits** Samantha McBride[1], Kripa K. Varanasi[1] and Rachael S. Skye[2]; [1]Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Michigan, United States; [2]Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Michigan, United States.

Evaporative deposits (for example, the well-known coffee-ring) are widely studied to improve technologies such as inkjet printing or to understand crystal fouling of infrastructure. Evaporative deposition can also be used as a tool for micro-scale assembly, as precipitates self-assemble into structures on extremely small length scales. Altering the conditions of evaporation allows for a large amount of control over the properties and structure of the resultant deposit. The morphology of inorganic crystalline patterns deposited from evaporating drops of saline solution are largely dependent on the wetting properties of the solid substrates they are placed on, with hydrophobic surfaces yielding localized deposits and hydrophilic surfaces causing larger, ring-shaped deposits. However, to date, little attention has been given to the role of surface energy on the crystal formation itself, with the crystal being treated as a simple product of the fluid flow rather than a separate entity that also interacts with the substrate chemistry. Here, we test the hypothesis that the surface energy of the burgeoning crystal faces will also contribute to the morphology of the crystalline deposits left from evaporating drops. To this end, experiments were performed on six different substrate chemistries. Substrate surface energy was analyzed by polar and non-polar components. We will show how the interactions between the growing crystals and the substrate affect the morphology of the resultant deposit. For drops containing colloidal nanoparticles, the deposit shows two modes, precipitating either in a ring or in a condensed disk, while drops containing crystals can also show intermediate modes of small or partial rings. These results have important implications for evaporative self-assembly as they present a method for tuning deposit morphology based on both substrate chemistry and the crystal chosen.

**BM09.08.20**
**Influence of the Formation Time of Amorphous $CaCO_3$ on Its Degree of Hydration and Stability** Huachuan Du[2], Mathias Steinacher[2], Camelia Borca[1], Thomas Huthwelker[1], Anna Murello[2], Francesco Stellacci[2] and Esther Amstad[2]; [1]Paul Scherrer Institut, Villigen, Switzerland; [2]Institute of Materials Science, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Calcium carbonate ($CaCO_3$) is an abundant biomineral that nature often uses as a structural material because of its excellent mechanical properties. Inspired by the excellent mechanical properties, a lot of work has been devoted to producing $CaCO_3$-based functional materials. However, the structures and properties of these biomimetic $CaCO_3$-based materials significantly differ from those of natural counterparts. To gain a closer control over the mechanical properties, a better understanding of the influence of processing conditions on the formation and stability of amorphous $CaCO_3$ (ACC) particles, that serve as transient precursors for $CaCO_3$ crystals, is crucial. Here, we I will present a new method to study the early stages of ACC particles formation using a microfluidic spray-dryer. The microfluidic spray-dryer forms $Ca(OH)_2$ containing aqueous drops that react with $CO_2$ and rapidly dry, thereby quenching the formation of ACC particles at early stages without the need of any organic solvent. We show that the amount of mobile water contained in ACC particles increases with increasing formation time and hence with increasing particle size. As a result, larger particles are less stable against temperature-induced solid-state crystallization and electron beam-induced decomposition than smaller counterparts. The amount of mobile water contained in ACC can be strongly reduced if certain organic additives, such as poly(acrylic acid) (PAA), is incorporated into ACC particles. As a result of the reduced mobility of water, these additive-stabilized particles are much more stable against crystallization and electron beam-induced decomposition. These insights might open up new opportunities to fabricate biomimetic $CaCO_3$-based materials with tunable structures and hence with properties that can be adapted to the specific needs of the different applications.

**BM09.08.21**
**Synthesis of Ion Substituted Ceramic Core-Shell Particles for Dental Applications** Camilla Berg, Wei Xia and Håkan Engqvist; Engineering Sciences, Uppsala University, Uppsala, Sweden.

Calcium phosphate spheres are interesting alternatives for dental applications due to their chemical similarity to teeth and biocompatibility.[12] A spherical shape with a hollow cores allows for loading of therapeutic agents for drug delivery which potentially could be combined with other applications such as tooth remineralization and treatment of hypersensitivity.[3]Precipitation reactions are one of the techniques used for synthesizing spherical particles, but little is known about the mechanism behind the sphere formation, which makes tuning of the material properties challenging. Previously, it has been shown that substituting ions can influence the crystallization process, which can enable greater control during the synthesis.[4] In this study, several different substituting ions has been used in the synthesis of alkaline earth phosphates, to further investigate their role in sphere formation and to develop a robust synthesis technique.

Particles of alkaline earth phosphates (Ca, Sr and Ba) were synthesized with a precipitation reaction. Solutions with constituent anions and cations were mixed at room temperature, and substituting ions (Mg, Ca or Sr) were added before heating at 60-100 °C. Reaction times varied between 10 minutes to 24 hours. Characterization of precipitates was performed with SEM, DLS and FIB to analyze morphology, size and cross-sections of the spheres. Crystal structure and atomic composition was analyzed with XRD and ICP-OES.

Without substituting ions, precipitates had no specific shape and crystallized in an apatitic structure or as a hydrogenated phosphate. Substituting ions stabilized the initial amorphous phase during the reaction, hindering rapid crystal growth which allowed for self-assembly into hollow, spherical particles with a diameter between 300-700 nm. The phase composition and degree of ion substitution in the precipitates depended on the size and concentration of the substituting ions. The amount of substitution was determined in the range between 5-30 %, where precipitates with a low degree of substitution crystallized in a structure similar to β-tricalcium phosphate, whereas materials with a higher degree of substitution had an amorphous structure.

In this study it was shown that it was possible to obtain hollow, spherical particles of calcium-, strontium- and barium phosphate, by using substituting ions during a precipitation reaction. This indicates that the approach can be used to tailor the properties of spherical particles intended for dental applications.

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**BM09.08.22**
**Self-Assembly of Nematic Liquid Crystals in Drops of Dried Lysozyme** Anusuya Pal and Germano S. Iannacchione; Physics, Worcester Polytechnic

Institute, Worcester, Massachusetts, United States.

In the recent years, an active area of research involves using liquid crystals (LCs), e.g. 5CB (4-Cyano-4'-pentylbiphenyl), for sensing biological and chemical analytes. Another active area of research studies drying drops of liquid revealing a rich interplay of fundamental mechanisms resulting in emergent patterns at the final dried state. In this presentation, these two areas are bridged by asking a basic question of the influence and the self-assembly, in the final dried state, of adding the liquid crystal, 5CB, with the initial protein solution of lysozyme and de-ionized water. The investigation is done using bright-field and cross-polarizing microscopy and quantified using image processing software- ImageJ and Fiji. It is observed that the crack patterns in the final dried state of the protein is influenced by the presence of small amounts of 5CB. Since the protein lysozyme is not birefringent, cross-polarizing microscopy closely monitors the distribution of the LC, while the bright-field microscopy probes the crack patterns that emerge. To understand the final deposits, the time evolution of the drying dynamics of the drops with and without 5CB are monitored. It is found in both drops that all the particles move to the drop edge due to convective flow, but with the LC, partial phase separation into droplets occurs while some LC remains mixed and dispersed into the channels formed by the protein particles. This work demonstrates the utility of using a bulk thermotropic LC as a probe material in a protein solution, revealing new information on the protein self-assembly during the drying process.

**BM09.08.23**
**Scalable Colloidal Self-Assembly by Deionization, Coacervation and Epitaxy** Rodrigo Guerra and Paul M. Chaikin; New York University, New York, New York, United States.

Charging and ionic conductance are ubiquitous properties of biomolecular and colloidal dispersions that also profoundly affect their stability and phase behavior. Rigorous deionization of macroions induces long-range electrostatic forces that can drive colloidal crystallization, and small changes in salinity can drive large changes in the assembly of oppositely charged particles, polyelectrolytes, and polyampholytes. Here we demonstrate a new technique to control the salinity of colloids and solutions in-situ, and show how it may be combined with polyelectrolyte coacervation and epitaxial templating to produce self-assembled crystals of oppositely charged colloidal particles using materials techniques that are inexpensive and scalable.

**BM09.08.24**
**Active Control of Calcium Carbonate Heterogenous Nucleation Using Mechanically Tunable Elastic Surfaces** Jay M. Taylor, Abhiteja Konda and Stephen A. Morin; University of Nebraska-Lincoln, Lincoln, Nebraska, United States.

Biological systems are capable of sophisticated and active control over the nucleation and growth of crystalline material. Their ability to control and direct the mineralization process enables the formation of intricate biological minerals with complicated micro-/nanoscale architectures with inimitable physical properties. Synthetic systems capable of such active control over crystal nucleation remain limited. Herein, a simple synthetic system that uses macroscopic physical strain in soft, elastic, silicone surfaces is used to control the rate of heterogeneous calcium carbonate nucleation in mild aqueous solutions. As the rate of heterogeneous nucleation is governed by the specific interfacial energies of system (i.e., calcite, water, and silicone surface), the application of mechanical stress to the chemically modified silicones alters the surface chemical composition and by relation the interfacial energies, thus altering the rate of heterogenous nucleation. In this system the rate more than doubles between the lowest and highest strain state on the silicone surface. The ability to tie nucleation rate to physical mechanical strain can enable temporal and spatial control over the nucleation process. The results presented herein provides a level of control over nucleation that has not yet been demonstrated, and will be of interest to those studying nucleation, biomineralization, and crystal engineering, and will have applications in adaptive materials, anti-fouling surfaces, and ice prevention.

**BM09.08.25**
**Amoeba-Like Self-Oscillating Polymeric Fluids with Autonomous Sol-Gel Transition** Michika Onoda[1], Takeshi Ueki[4], Ryota Tamate[2], Mitsuhiro Shibayama[3] and Ryo Yoshida[1]; [1]The University of Tokyo, Tokyo, Japan; [2]Yokohama National University, Kanagawa, Japan; [3]Institute for Solid State Physics of the University of Tokyo, Chiba, Japan; [4]National Institute for Materials Science, Ibaraki, Japan.

One of the important feature of living organisms is the dynamic behavior based on the hierarchical spatio-temporal structuration of building blocks driven by chemical signals. For example, spontaneous assembly and disassembly of actin networks play a central role in muscle contraction, cell division, and motility of protists. Despite these concepts are widely accepted as key components of biological systems, there are few reports that reproduce the dynamic behaviors based on the hierarchical spatio-temporal structuration by using only synthetic materials.
In contrast, we have reported structural oscillations of micelles and vesicles by totally synthetic AB diblock copolymer (di-BCP) incorporated a catalyst site of the Belousov-Zhabotinsky (BZ) reaction, without applying any on-off switching. In addition, we recently succeeded in realizing autonomous viscosity oscillation induced by microscopic self-oscillation between formation and break-up of the micellar network structure by preparing ABA tri-BCP. However, the viscosity amplitude was still limited (~2 mPa s).
Herein, we describe the self-oscillating ABC tri-BCP exhibiting autonomous sol-gel transitions assisted by dynamic structural oscillations between association and dissociation of the percolated network structure similar to a living amoeba. The target multiblock copolymer is synthesized by sequential reversible addition-fragmentation transfer (RAFT) polymerization incorporating a thermoresponsive A segment, a hydrophilic B segment, and a self-oscillating C segment. Unique oscillation behaviors of the multiblock copolymer are investigated in terms of time-resolved dynamic light scattering techniques for a dilute polymer solution and dynamic viscoelastic measurements for a concentrated polymer solution. As a result, novel oscillation behaviors among large viscosity oscillation, sol-gel oscillation, and viscoelastic oscillation are successfully demonstrated. The maximum amplitude of the viscosity is about 2,000 mPa s, which is 1000 times larger than previous report and equal to the oscillation amplitude in a living amoeba. We also demonstrate an intermittent forward motion of a droplet of the polymer solution synchronized with the autonomous sol-gel transition. This marvelous polymer solution bears the potential to become the base for a type of slime-like soft robots that can transform their shape kaleidoscopically and move autonomously, which is associated with the living amoeba that move forward by a repeated sol-gel transition.

SESSION BM09.09: In Situ Characterization and Biomimetic Crystallization
Session Chairs: Marc Knecht and Nico Sommerdijk
Thursday Morning, November 29, 2018
Sheraton, 2nd Floor, Back Bay A

**8:00 AM *BM09.09.01**
**How Do Organic Additives Control Multistep Nucleation?** Alexander E. Van Driessche; CNRS - Univ. Grenoble-Alpes, Grenoble, France.

In the idealized laboratory environment crystallization from pure solutions can follow either a single or a multistep nucleation pathway. The latter case involves the formation, aggregation and transformation of precursor particles to the final crystals [e.g. 1-3]. But, in most natural and industrial crystallization environments additives play a key role and are a central part of biomineralization, of functional material synthesis or of anti-scaling strategies, to name just a few. To gain full understanding and therefore control over crystallization, the possible interactions between additives and the precursor particles, intermediate and final phases need to be precisely unraveled.
In order to elucidate how additives get the job done we studied *in situ* and at the nanoscale the early stages of mineral formation in the presence of additives and compared them to the pathway observed for the additive free system [e.g. 4,5]. In this presentation, an overview of nucleation in the presence of additives will be given. Special emphasis will be placed on the interaction of organic molecules with precursor particles and how this affects the dynamics of the nucleation pathway.

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**8:30 AM BM09.09.02**
***In Situ* Liquid Transmission Electron Microscopy to Follow Liquid-Liquid Phase Coacervation** Hortense Le Ferrand, Martial Duchamp, Bartosz Gabryelczyk, Cai Hao and Ali Miserez; Nanyang Technological University, Singapore, Singapore.

Liquid coacervate is a metastable state where biopolymers assemble into densely packed droplets of low interfacial energy. In biology, coacervates may form inside the cells under variation of physiological conditions, for example under chemical stress [1]. Liquid coacervates form through spinodal decomposition but yet little is known about the path by which coacervate micro-droplets are formed: nucleation and growth, coalescence of smaller droplets, or formation of intermediate states? Here, we use as a model system a protein from the squid beak (HBP-2), whose recombinant version was recently shown to exhibit coacervation triggered by variations of pH and ionic strength [2]. Optical observations indicate that far from the spinodal conditions, coacervation occurs after a lag time and exhibits a linear increase in droplet density. Furthermore, time-dependent circular dichroism reveals that droplet formation coincides with the folding of HBP-2 into ß-rich structures. Finally, direct observations under liquid transmission electron microscopy (liq-TEM), shows the nucleation of droplets of 1.5 to 2 nm in diameter, 20 nm entities and a network-like structure. At high ionic strength, the hydrogel-type of network shrinks, leading to the formation of dense discrete droplets. To the best of our knowledge, our study is the first example of *in-situ* observation of liquid-liquid phase separation under TEM. Understanding the precise assembly pathway of proteins into coacervates may help developing tools to prevent its occurrence when coacervates are the precursors of phases (such as amyloids) associated with pathological diseases [1].

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**8:45 AM BM09.09.03**
**Interfacially-Driven Nanoparticle Nucleation—A New Pathway to Mesocrystal Formation** Guomin Zhu[1, 2], Maria Sushko[2], Jinhui Tao[2], John Loring[2], Benjamin Legg[1], Jennifer Soltis[2], Chongmin N. Wang[2] and James J. De Yoreo[1, 2]; [1]University of Washington, Seattle, Washington, United States; [2]Pacific Northwest National Laboratory, Richland, Washington, United States.

A diverse class of materials, including many biominerals, exhibit characteristics of mesocrystals: single crystals composed of distinct nano-sized domains that are atomically aligned. The formation of such structures is often attributed to crystallization through oriented attachment (OA). However, many unanswered questions about the fundamental drivers and dynamic progression of this processes remain. Here we focus on the crystallization of hematite (hm, $Fe_2O_3$) from ferrihydrite (fh) as an example. In pure solution the resulting hm crystals are well faceted cuboctahedra, but in the presence of oxalate hm forms a nanoporous spindle-shaped single crystal elongated along [001]. The spindles are hierarchically organized at two length scales. At the shortest length scale, they consist of atomically aligned nanometer size domains. These then form a second order structure consisting of chains of the hm domains. Multiple techniques including liquid cell AFM and TEM were used to probe the process by which these mesocrystals form. In addition, we developed a freeze-and-look approach using indexed TEM grids to cycle samples between the growth reactor and the TEM in order to track the pathway of crystallization at identical positions over time. We identified two important processes. First, the transformation from fh to hm is highly localized, with the initial hm particles nucleating on the surface of fh. Second, the porous spindle hm mesocrystal forms by nucleation of new hm particles at the hm/solution interface, followed by attachment to the adjacent particle. The preference for growth near the (001) end of the spindle leads to the self-similar growth of the aggregate. Moreover, growth from a dense region of fh primary particles leads to formation of half-spindles growing into the free solution. Based on ATR-FTIR measurements of the relative binding strength of oxalate to the (001) and (012) faces, and calculations of chemical potential gradients near the interface, we propose that oxalate plays the role of inhibiting classical monomer-by-monomer growth of the hematite particles while promoting the nucleation of new hm particles at the hm/solution interface. Consequently, by inhibiting classical growth and driving all nucleation to occur near existing hm particles, the ligands bias the growth process towards oriented attachment. The common observation of crystals that appear to have formed via OA in solutions that are largely devoid of individual particles, suggesting this growth scenario may be widespread.

**9:00 AM BM09.09.04**
**Negative Poisson's Ratio of a Natural Nanocomposite Studied by *In Situ* TEM Mechanical Testing** Jinkyung Kim, Jinsol Seo, Jiwon Jeong, Jeehun Jeong, Zhen Wang and Sang Ho Oh; Sungkyunkwan University, Suwon, Korea (the Republic of).

The teeth of limpets are reported to be the strongest natural material, with tensile strength values ranging from 3 to 6.5 GPa. However, the origin of ultrahigh strength of limpet teeth is still unknown. Limpets use conveyor belt-like radula to scrape rocks and extract algae during feeding. These processes require extremely strong teeth. Limpet teeth show characteristic composite nanostructures consisting of high volume fraction of reinforcing goethite crystals and softer amorphous hydrated silica matrix. The volume fraction and morphology of goethite crystals are heterogeneous at different locations of the tooth, which leads to site-specifically heterogeneous mechanical properties. The present work reports on the relationship between microstructures and deformation mechanisms of limpet teeth, using transmission electron microscopy (TEM) and in-situ TEM deformation. At the leading part of a limpet tooth, goethite crystals are mainly aligned along the principal direction of a tooth. The goethite crystals are rod-shaped, with approximately 30 nm in diameter and 300 nm in length. The volume fraction of the goethite crystals is approximately 50 %. TEM characterization of a longitudinal section at the tip of a limpet tooth shows both normally and laterally aligned goethite crystals, with some clusters of the normally aligned crystals. In addition, transition areas at the interfaces between goethite crystals and amorphous matrix are frequently observed. Atomic scale scanning transmission electron microscopy (STEM) and electron energy loss spectroscopy (EELS) analyses show that the transition areas have different atomic structures and chemical composition

from the original goethite crystals. The trailing part of a limpet tooth shows larger goethite crystals, with lower volume fraction than the leading part. To understand deformation behavior of limpet teeth, in-situ TEM deformation experiments were conducted using the samples taken from the tip of a limpet tooth. Upon tension, the sample shows both positive tensile and transverse strain, which indicates negative Poisson's ratio. The rotation of laterally-aligned goethite crystals appears to result in observed negative Poisson's ratio. When the sample fractures, a crack propagates very fast right after its initiation. The ultrahigh strength of limpet teeth is expected to delay initiation of cracks. The present work will discuss the relationship among microstructures, deformation/fracture behavior and mechanical properties of limpet teeth. This could provide an insight into design of bioinspired engineering composite materials with superior strength and toughness.

**9:15 AM BM09.09.05**
**Barrier-Free Nucleation of 2D Phage-Selected Peptide Films on $MoS_2$ Surfaces** Jiajun Chen[1, 2], Enbo Zhu[3], Juan Liu[4], Hendrik Heinz[4], Yu Huang[3] and James J. De Yoreo[1, 2]; [1]University of Washington, Richland, Washington, United States; [2]Pacific Northwest National Laboratory, Richland, Washington, United States; [3]University of California, Los Angeles, Los Angeles, California, United States; [4]University of Colorado Boulder, Boulder, Colorado, United States.

Directed assembly of two-dimensional molecular arrays on crystal surfaces has been widely investigated to reveal the structural and energetic relationships between the substrate and overlying architecture. Progress has been achieved in understanding and controlling their assembly, yet little is known about the mechanism by which they nucleate. Understanding the dominant pathways and formation kinetics would enable precise control over phase and morphology during synthesis of 2D materials. In our study, short peptides were selected for their ability to bind to $MoS_2$(0001). We studied nucleation and growth of 2D films of these peptides directly with *in situ* atomic force microscopy and compared our results to molecular dynamics simulations. We find the peptide arrays exhibit an epitaxial relationship to the underlying hexagonal lattice, but assemble one row at a time from dimeric units, and grow along three equivalent directions. The nuclei are ordered from the earliest stages without evidence for a transient precursor phase. Although the final crystals are 2D, due to the 1D nature of the constituent rows, there is no critical size, and the nucleation rate varies linearly with concentration and is finite for all concentrations above the solubility limit. Our results verify long-standing but unproven predictions of classical nucleation theory while revealing the key interactions responsible for ordered assembly.

**9:30 AM BREAK**

**10:00 AM *BM09.09.06**
**The Influence of Structural Factors, Conformational Dynamics and Solvent Effects on Macromolecular Self-Assembly** James J. De Yoreo; Pacific Northwest National Laboratory, Richland, Washington, United States.

Self-assembled macromolecular architectures exhibit a range of structural motifs such as particles, fibers, ribbons and sheets with functions that include selective transport, structural scaffolding and mineral templating. Although the sequence of the molecules dictates their governing interactions, function emerges from the mesoscale organization that arises from assembly. In the classical picture of assembly, order develops concomitantly with condensation as part of the microscopic density fluctuations inherent to all systems. However, establishment of long-range order in macromolecular structures almost always requires significant changes in conformation away from that seen in the monomeric state. Moreover, the presence of hydrophobic regions drives aggregation events that compete with ordered assembly. The impact of such structural transformations and transient states on the assembly process are a current subject of intense research. Using *in situ* techniques including AFM and optical and dynamic force spectroscopy, we have investigated the dynamics of assembly and intermolecular interactions for a number of natural protein and synthetic sequence-defined polymer systems assembling from solution on surfaces. In non-rigid systems, the results show that conformational transformations impose kinetic limitations on the nucleation of order. Transient fluctuations no longer provide a pathway to order; instead, the system must be driven to stabilize amorphous or liquid-like precursors. Moreover, once ordered structures nucleate within these precursors, conformational changes of the remaining solution-phase monomers are catalyzed by the presence of the ordered nucleus. However, the final architecture depends strongly on the interplay between protein-protein, protein-surface, and protein-solvent interactions. In particular, the introduction of high salt concentration, which screens electrostatic repulsion and introduces large entropic effects, leads to ordering processes reminiscent of colloidal systems. Small changes in sequence that alter the balance of hydrophobic and electrostatic interactions can induce a switch in assembly pathway between the multi-stage process described above and direct formation of the ordered structure. Finally, building 2D structures at interfaces out of molecules that assemble one row at a time, eliminates the barrier to nucleation and creates an asymmetry in nucleation kinetics for the first row and all subsequent rows, creating a simple means to tune the aspect ratio of the resulting 2D materials. The results of these studies suggest that the requirement of conformational transformation introduces a timescale for structural relaxation that differs from that of the density fluctuations and thus alters the pathway and kinetics of assembly, but that the details of macromolecular sequence, solvent interactions, and the architecture of the ordered phase can be used to influence barriers, pathways and outcomes.

**10:30 AM BM09.09.07**
***In Situ* Atomic Force Microscopy of DNA-Mediated Nanoparticle Assemblies in Solution** Mikhail Shekhirev, Eli Sutter and Peter Sutter; Univ of Nebraska-Lincoln, Lincoln, Nebraska, United States.

Self-assembly of nanoparticles into crystalline superlattices is an attractive approach toward fabricating metamaterials with tunable properties. Synthetic DNA as a "bonding agent" provides programmable crystallization of nanoparticle superlattices according to well-defined rules [1]. Remarkable progress has been made in fabricating 3D architectures with different crystal symmetries and consisting of different building blocks. Recently, research interest has shifted towards tuning structural parameters of the superlattices in response to external stimuli to creative adaptive materials architectures. Techniques for following such complex processes in the native solution environment have so far been limited mostly to X-ray scattering methods, with real space imaging (e.g., by liquid cell electron microscopy [2,3]) still in its infancy.
Here we present results of an investigation of DNA-mediated nanoparticle superlattices using in-situ atomic force microscopy (AFM). AFM is a powerful technique for direct imaging of soft samples, including DNA, in solution. However, AFM on DNA-bonded nanoparticle superlattices is challenging due to the weak base-pairing interaction between oligonucleotides and possible damage by the scanning probe. We demonstrate that by using peak-force tapping with precise control over the imaging forces, we can achieve continuous imaging without any significant perturbation of the nanostructures. Such non-invasive imaging in solution revealed a close-packed hexagonal arrangement of nanoparticles in surface-bound single- and few-layer superlattices. In contrast to diffraction, direct imaging of the assemblies allows the identification of particle arrangements within individual ordered and disordered domains, thus providing local information not accessible in reciprocal space. This approach shows systematic differences in the equilibrium distance of the DNA-coupled nanoparticles, for example in different layers of multilayer crystals or between central and edge regions in single-crystalline monolayer domains. Finally, we discuss in-situ AFM experiments toward understanding the reconfiguration of DNA-mediated nanoparticle superlattices in response to external stimuli, e.g., changes in solvent polarity and addition of DNA intercalants. Our in-situ real-space observations provide unprecedented insight into the behavior of DNA-nanoparticle conjugates as "programmable atom equivalents".
[1] S.Y. Park et al., *Nature* **451**, 553 (2008).
[2] E. Sutter et al., *Nature Communications* **7**, 11213 (2016).

[3] P. Sutter et al., *Nanoscale*, submitted (2018).

**10:45 AM BM09.09.08**
**Towards Collagen—Zinc Oxide Hybrid Materials** Mark M. van Rijt[1, 2, 3], Heiner Friedrich[1, 2, 3] and Nico Sommerdijk[1, 2, 3]; [1]Laboratory of Materials and Interface Chemistry and Centre for Multiscale Electron Microscopy, Eindhoven University of Technology, Eindhoven, Netherlands; [2]Chemical Engineering and Chemistry, Eindhoven University of Technology, Eindhoven, Netherlands; [3]Institute for Complex Molecular Systems, Eindhoven University of Technology, Eindhoven, Netherlands.

In biology hierarchical organic-inorganic composites show highly tailored properties due to their precise control over shape and structure. One example is the mineralization of collagen with calcium phosphate in bone which results in remarkable mechanical properties. Its highly-defined pores make collagen a template of interest for more inorganic phases than only calcium phosphate.

One of these inorganic phases is Zinc oxide (ZnO). ZnO is a metal oxide with a range of electro and opto-electronic properties, among them piezo-electric behavior. By mineralizing ZnO in the confinement of collagen enhanced and selective control of its piezo-electric behavior should be achievable. ZnO has previously been synthesized under mild “bio-friendly” conditions using hydrothermal synthetic strategies; aqueous environment, low temperature (50 – 80 ºC) and ambient pressure. However, the initial stages and the mechanism of ZnO formation are rather poorly understood, making the incorporation of ZnO into collagen at this stage rather challenging.

The current steps in this work therefore focus on understanding the initial stages of ZnO formation. Preliminary results using conventional transmission electron microscopy (TEM), cryogenic TEM (cryoTEM) and selected area electron diffraction (SAED) studies suggest a multi-step precursor assisted mechanism. The formation of a nano-platelet precursor phase is observed by cryoTEM within the first minutes, showing no crystallinity with SAED. These platelets evolve into irregular sheets. At this stage nucleation of ZnO particles ~ 2-3 nm in diameter on the surface of the precursor sheets is observed, with SAED confirming the presence of ZnO. These primary particles subsequently grow into ZnO pillars via participle attachment.
By elucidating this mechanism of formation using advanced cryoTEM and liquid phase TEM studies and by further studying the use of charged polymers and polypeptides as crystallization directing agents, we aim at obtaining new insights for the design and formation of collagen – ZnO hybrid materials.

**11:00 AM BM09.09.09**
**Iron Sulfide Supraparticles as Artificial Viruses for Gene and Gene Editing Therapies** Emine Turali-Emre, Ahmet Emre and Nicholas A. Kotov; University of Michigan–Ann Arbor, Ann Arbor, Michigan, United States.

Gene and gene editing therapies have been widely investigated for treatment of inherited or acquired genetic diseases. Efficient delivery of therapeutic agents has become a significant barrier in clinical applications due to the toxicity and instability of the vectors in the complex intracellular environment. Among non-viral vectors, individual inorganic nanoparticles (NPs) have become a popular strategy for nucleic acid delivery. However, the nanoshell geometry of viruses is advantageous for the gene/CRISP cargo protection. Therefore, we synthetized L-cysteine stabilized iron-based inorganic nanoparticles which self-assemble into supraparticles with nanoshell geometry. Transmission electron microscopy (TEM), TEM tomography and dynamic light scattering (DLS) were used to characterize the virus-like supraparticles' size, shape, and charge. Our results indicate that virus-like supraparticles contain continuous compartments, are positively charged (25±7.2 mV) and 74±21 nm in diameter. We loaded the DNA in the compartments during the formation of supraparticles. We tested these complexes in circular dichroism, UV-Vis spectroscopy, electrophoretic mobility shift and protection assays. Since iron sulfide is a natural material, it presumably has low cytotoxicity and high biocompatibility. Supraparticles can condense DNA, protect it against degradation, penetrate through cellular membranes and facilitate endolysosomal escape in gene therapy. Therefore, development of these particles can be used as an effective cargo delivery tool for gene and gene editing therapies.

**11:15 AM BM09.09.10**
**Biomimetic Molecularly Imprinted Photonic Crystal for Small Molecule Detection** Prathyushakrishna Macha[1], Abigail Juhl[2] and Milana C. Vasudev[1]; [1]University of Massachusetts Dartmouth, Dartmouth, Massachusetts, United States; [2]Materials and Manufacturing Directorate, Air Force Research Laboratory, Dayton, Ohio, United States.

In recent times, an increase in opioid related deaths have occurred due to the addition of synthetic opioids such as Fentanyl and carfentanil. Though there are conventional techniques, they are not designed for on-site detection of these molecules and are tedious. Photonic crystal structures have garnered significant interest in the fields of antireflective coatings, gas sensors, omnidirectional mirrors and label-free biological sensing. These have advantage over the conventional techniques as the structural enhancement and local changes in the refractive index (RI) allows for highly sensitive label-free onsite small molecule detection. The species *Beroe Cucumis* and *Mnemiopsis Leidyi* of phylum Ctenophora have two-dimensional (2D) photonic crystals in their combs, which occur relatively less frequently in nature. The structures which occur in the ctenophores were studied by embedding and morphology studies using cross-sections created using an ultratome and studied them to understand the nanoscale arrangements with the help of a transmission electron microscope.

Two-photon lithography, ebeam lithography, and nanoimprint lithography, were used to replicate these arrangements. The photonic crystal templates formed were observed using scanning electron microscopy and their reflectivity, Raman scattering, refractive indices were analyzed and further used for designing a molecularly imprinted photonic crystal (MIPC) to detect the target molecules as a colorimetric sensor.

**11:30 AM BM09.09.11**
**3D Self-Assembly of Nanocrystals via Co-Crystallization with Proteins** Hyewon Kim, Xiaoting Guo, Yasutaka Nagaoka, Ou Chen and Vicki L. Colvin; Department of Chemistry, Brown Univ, Providence, Rhode Island, United States.

It has been a challenge to develop a facile and versatile method to achieve the 3D arrangement of nanocrystals. On the other hand, nature utilizes self-assembly process to produce the complex structured functional materials. Here, we present how the process of protein crystallization can provide a means for achieving the 3D arrangement of nanocrystals. By controlling the interaction between nanocrystals and protein, we achieved incorporation and the 3D arrangement of nanocrystals within protein crystals.
We chose hen egg white lysozyme (HEWL) and gold nanocrystals as a model system. For co-crystallization, weak attraction between nanocrystals and HEWL is required. We controlled interaction between gold nanorods (AuNRs) and hen egg white lysozyme (HEWL) by functionalizing AuNRs with poly (ethylene glycol) (PEG). When gold nanorods are functionalized with large molecular weight PEG, weak attractive interaction between AuNRs and HEWL arises. This weak interaction leads to facilitate nucleation of HEWL crystals and incorporation of AuNRs into HEWL crystals. Controlling directed self-assembly of nanoparticles requires understanding interactions between nanoscale building blocks. We used HPLC to understand the interaction between the gold nanocrystals and HEWL. Single crystal x-ray scattering confirms that the lattice parameter of HEWL is preserved when AuNRs are incorporated. We used SAXS, TEM, and the polarized optical microscopy to show that AuNRs are incorporated into lysozyme crystals and AuNRs inside the crystals have

some ordered arrangement within HEWL crystal structure.
The phenomenon was independent of nanoparticle shape and type. We found other nanoparticles, such as iron oxide, quantum dots, and spherical gold nanoparticles also proceed co-crystallization with HEWL when the surface grafting density of PEG was low. This confirms that the surface properties of NP-PEG conjugates, rather than the nanoparticle itself, dictates the protein-nanoparticle solution interactions and the subsequence incorporation of nanoparticles into biomolecular crystals. In addition, proteins other than HEWL shows co-crystallization with these NP-PEG conjugates, which indicates this process can be applied to various 3D arrangement of nanocrystals.

**11:45 AM BM09.09.12**
**Bioinspired Templating and Assembly of Heme Crystals for High-Performance Energetic Materials** Chia Hung[1], Andrea R. Poole[1, 2], Joseph Slocik[1, 2], Rajesh Naik[1], Patrick B. Dennis[1], Wendy J. Crookes-Goodson[1] and Maneesh K. Gupta[1]; [1]Air Force Research Laboratory, Wpafb, Ohio, United States; [2]UES, Inc., Dayton, Ohio, United States.

Thermite reactions with nano-scale particles have attracted much study due to their high flame temperatures and combustion velocities. Mixing chemically synthesized heme crystals (hemozoin) with aluminum nanoparticles (nAI), Slocik and co-workers (Slocik, 2015) demonstrated nanocomposites with increased energy output and combustion rates. Hemozoin are naturally produced by malaria parasites *Plasmodium falciparum* through bio-templated crystallization of heme B by Histidine-Rich Protein II (HRPII). Proteins with high histidine content with metal-coordinating functions are present in many organisms, including the *Nereis virens* jaw protein 1 (Nvjp1). Although rich in histidine and natively found to coordinate Zn(II), Nvjp1 does not share similar histidine-repeat motifs as HRPII. Here, we demonstrate the ability of Nvjp1 proteins to template hemozoin formation. Recombinantly produced Nvjp1 was incubated with iron-containing heme and efficiently formed hemozoin crystals. X-ray diffraction confirmed the crystal structure of the templated hemozoin crystals. Additionally, Nvjp1 was utilized to assemble hemozoin crystals directly on the surface of nAl yielding thermite nanocomposites. Results demonstrated that hemozoin formation is feasible with orthogonal proteins, therefore expanding the repertoire of candidates for bio-templated heme crystal formation. Through engineering of these proteins, the ability to control the size and shape of hemozoin crystals and hence the energy output of thermite nancomposites could be realized.

Reference:
Slocik JM, Drummy LF, Dickerson MB, Crouse CA, Spowart JE, and Naik RR. Bioinspired High-Performance Energetic Materials Using Heme-Containing Crystals. Small. 2015, pp. 3539–3544.

SESSION BM09.10: Theory Driven Design
Session Chairs: Alexander Van Driessche and Tiffany Walsh
Thursday Afternoon, November 29, 2018
Sheraton, 2nd Floor, Back Bay A

**1:30 PM *BM09.10.01**
**Analysis of the Surface-Accessibility of Matrix-Tethered Peptides in Peptide-Functionalized Hydrogels by Multiscale Molecular Simulation** Robert A. Latour, Xianfeng Li, Jia Jia and Ying Mei; Clemson University, Clemson, South Carolina, United States.

Poly(ethylene glycol)-based hydrogels conjugated with peptides are being developed for tissue engineering, regenerative medicine, drug delivery, and biosensor applications. The bioactivity of peptide-conjugated hydrogels depends on the accessibility of the tethered peptides at the hydrogel surface in order for them to carry out their intended bioactive function (e.g., cell-receptor binding). As a copolymer system, the presence of the peptide at the hydrogel surface is dependent on the concentration of the peptide in the hydrogel, the tether length and composition, and the thermodynamics controlling the partitioning of the tethered peptide within the hydrogel matrix. This partitioning is difficult to assess experimentally, with experimental methods essentially being limited to trial-and-error-based approaches (e.g., combinatorial methods) for hydrogel design to optimize bioactivity. To provide insight into the thermodynamic behavior of peptide-functionalized hydrogels, we developed multiscale molecular modeling methods to visualize, predict, and understand their molecular structure and the surface accessibility of tethered peptides as a tool for hydrogel design optimization. The modeling approach involves: (1) on-lattice modeling at experimentally determined cross-link density, (2) off-lattice coarse-grained modeling to efficiently equilibrate the system, and (3) reverse-mapping the equilibrated CG models to all-atom models with final equilibration. Model validation included comparison with X-ray structure-factor analyses. The resulting coarse-grained and all-atom models were analyzed to characterize the distribution of the peptides within the hydrogel and their accessibility and structure at the hydrogel surface. CG and all-atom modeling is performed based on the PCFF force field along with TIGER2A accelerated sampling for efficient equilibration. This work was supported by “RESBIO—The National Resource for Polymeric Biomaterials” funded under NIH Grant No. P41 EB001046, NIH Grant No. P20GM103444, and the Center for Advanced Fibers and Films (CAEFF) at Clemson University, Clemson, SC, USA. Computational support was provided by the Palmetto High Performance Computing Resource at Clemson University, Clemson, SC, USA.

**2:00 PM BM09.10.02**
**Multiscale Model of Human Elastin** Anna Tarakanova; Department of Mechanical Engineering, University of Connecticut, Storrs, Connecticut, United States.

Elastin is the dominant building block of elastic fibers that impart structural integrity and elasticity to a range of important tissues, including the lungs, blood vessels and the skin. The elastin polymer is assembled from its molecular precursor tropoelastin. Historically, elastin’s dynamic nature has precluded traditional approaches such as X-ray crystallography to understand its detailed features. Here, I describe recent work using atomistic and coarse-grained models for predicting elastin’s multiscale structure and mechanical properties. We use the models to probe the function of key molecular regions, investigate disease etiology and explore implications for hierarchical assembly. The elastic fiber assembly process begins with a coacervation stage where monomers reversibly self-assemble into n-mer structures. Starting with the monomer as the basis for coarse-graining, we map the atomistic model to a MARTINI-based coarse-grained framework fortified with an elastic network. We show that directed assembly takes place through nucleation events and resulting aggregates display preferential domain positioning for enhanced cross-linking. Our results suggest that the irreversible coalescence of n-mer assemblies into higher-order fibrillar structures may be reinforced in the initial stages of coacervation by directed assembly.

**2:15 PM BM09.10.03**
**Designing Hybrid Biological Materials—Controlling Morphology via Molecular Composition** Srinivas Mushnoori[1], Kassandra Schmidt[1], Vikas

Nanda[2] and Meenakshi Dutt[1]; [1]Biomedical Engineering, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States; [2]Center for Advanced Biotechnology and Medicine, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States.

Peptide self-assembly is a field that shows great promise in the domain of controllable and shape tunable biomaterials. Their unique properties allow for a building blocks approach to materials design. In this study, mixed systems of two carefully selected peptides (i.e. diphenylalanine and phenylalanine-asparagine-phenylalanine) are explored for their self-assembly properties. We report a rich polymorphism in the assemblies of these peptides and explain the relationship between peptide molecular structure and the morphology of supramolecular assembly.

**2:30 PM BM09.10.04**
**Simulating the Effect of Organic Molecules on Clustering in Calcium Carbonate and pHosphate—A Key Stage in Biomineralisation** Aaron Finney[1], Riccardo Innocenti Malini[2], Colin L. Freeman[1] and John H. Harding[1]; [1]University of Sheffield, Sheffield, United Kingdom; [2]Empa, Swiss Federal Laboratories for Materials Science and Technology, St. Gallen 9014, Switzerland.

Calcium carbonate and calcium phosphate are the most important biominerals in nature but there is still no consensus on how they form. Many nucleation and growth mechanisms have been and continue to be proposed. An amorphous phase is known to precede both crystalline carbonate and phosphate phases. It is also known that both inorganic and organic additives can affect the crystallisation process, the polymorphs formed, and the physical properties of the resulting materials. Simulations have frequently been used to try to unravel the complex mechanisms involved but require considerable computer resources to reach the long timescales required.

Recent work on calcium carbonate solutions at low concentration in the presence of amino acids has shown that they exhibit behaviour typical of that expected by classical nucleation theory with free ions, ion pairs and other small clusters present. At high concentration the amino acids self-assemble into aggregates, facilitated by ‘spectator’ ions and usually by bicarbonate ions. Liquid-like clusters form from the remaining calcium carbonate. These are also seen at the surface of the amino acid aggregates. When simulations are performed in the presence of oligopeptides (amino acid hexamers) liquid-like networks are formed, seeming to stabilise a dense liquid phase. Calcium phosphate also forms liquid-like clusters in the presence of amines, in this case the buffer tris(hydroxymethyl)aminomethane (TRIS). The simulations suggest that TRIS favours the formation of negatively charged complexes, and we believe that these are responsible for the inhibitory effect of TRIS. More generally, the formation of charged large aggregates could explain the formation of dense liquid phases in phosphate solutions.

We discuss the implications of these results for the role of a dense liquid phase in the nucleation mechanism for calcium carbonates and phosphates, connecting with the long-established proposal by Gower of the importance of a polymer-induced liquid phase (PILP) in the nucleation of biominerals.

**2:45 PM BM09.10.05**
**Understanding Polymorph Selection in Calcium Carbonate** Colin Freeman[1], Aaron Finney[1], Riccardo Innocenti Malini[2] and John H. Harding[1]; [1]University of Sheffield, Sheffield, United Kingdom; [2]Empa, Swiss Federal Laboratories for Materials Science and Technology, St Gallen, Switzerland.

Within biomineralisation we frequently see the expression of both calcite and aragonite with the later being common in many marine organisms probably due to its enhanced material properties. These two polymorphs are very similar and differ only marginally in thermodynamic stability to favour calcite [1]. Despite its abundance in the natural world, aragonite is difficult to synthesise in the lab, requiring Mg or other additives. An alternative method is to raise the solution temperature above 70$^{O}$C [2] despite the fact that the actual thermodynamic stability is unchanged at this these temperatures. The lack of aragonite and even its general absence from a solution during crystallisation implies that the nucleus must be unstable and quickly dissolve. This is at odds with recent simulation work that demonstrates that the surfaces of aragonite may be more stable in water than their calcite counterparts [3]. Computational molecular dynamics provides an ideal tool to study this unusual phenomena. We have studied the interfacial energies of a range of calcium carbonate polymorphs in contact with water and amorphous calcium carbonate with varying water concentrations. We use this data to demonstrate the stability of the different calcium carbonate nuclei. Using a statistical analysis of the structure we are able to identify the first stages of nuclei formation and discuss the potential structural features of these. This investigation reveals that kinetics rather than thermodynamics may be dictating the phase selection.

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**3:00 PM BREAK**

**3:30 PM BM09.10.06**
**Hierarchical Assembly of Computationally Designed Coiled Coils into Tunable 1D Architectures** Nairiti J. Sinha[1], Dongdong Wu[1], Chris Kloxin[1], Jeff Saven[2] and Darrin J. Pochan[1]; [1]University of Delaware, Newark, Delaware, United States; [2]University of Pennsylvania, Philadelphia, Pennsylvania, United States.

Computational design guided self-assembly of biomolecules such as peptides has emerged as a new paradigm for engineering novel biomaterials in a bottom-up fashion. We exploit hitherto computationally designed homotetrameric antiparallel coiled coils as modular cylindrical Legos for assembling hierarchical 1D architectures using a hybrid physical-covalent assembly pathway. Specifically, the coiled coils are functionalized at the N-termini with either thiol-containing cysteine or maleimide functional groups and subsequently linked together via the Thiol-Michael 'click' reaction to form novel 1D chains of coiled coils. While the aspect ratio of these chains can be easily manipulated by changing the stoichiometric ratio of cysteine to maleimide functionalized coiled coils, the flexibility of the chains can also be tuned by the linker type between the coiled coils. Thus, a short linker results in stiff rods with large persistence lengths while a longer flexible linker yields flexible fibers, both of which are clearly visible in Transmission Electron Microscopy (TEM) analyses. Small Angle Neutron Scattering (SANS) has confirmed that these 1D chains of coiled coils are ca. 2 nm in diameter that is comparable with the designed cross-section of a coiled coil. Furthermore, stiff rods that are ca. 100 nm in length form liquid crystal domains at high concentrations that have a smectic like birefringence texture. The addition of sodium chloride salt changes the liquid crystal phase to one having a mosaic like birefringence texture. We propose that this is because the rods are net negatively charged in pure water and addition of salt screens the charge on the rod exterior which results in the observed change in the liquid crystal phase. This is supported by SANS of rods which exhibits a correlation hole in the intensity curve due to repulsion between rods in low ionic strength solution which disappears when salt is added.

**3:45 PM BM09.10.07**
**Computational Design of Hierarchically-Assembled Multi-Component 2D Protein Materials** Ariel J. Ben-Sasson[1], William Sheffler[1, 2], David Baker[1], Fang Jiao[2] and James J. De Yoreo[2]; [1]Biochemistry, University of Washington, Seattle, Washington, United States; [2]Physical Sciences, Pacific Northwest

National Laboratory, Richland, Washington, United States.

The major advances in computational engineering of symmetric protein assemblies and characterization methods forms the basis for the design of novel materials, systems, and devices. A grand challenge that remains is the ability to generate multi-components assemblies with unbound symmetry that could theoretically grow infinitely either in vivo or in vitro. In other words, the challenge is to design protein components that would never self-assemble but co-assemble under a variety of conditions: in living cells, Eppendorf tube, or an advanced 3D printer.
In this work, we developed a computational method for the design of multi-component 2D protein assemblies by combining a number of design principles:
Introducing plane symmetry constraints into the Rosetta software suite to engineer assembly pathways for hierarchical assembly of protein arrays.
Computational interface design of multiple non-covalent, weak, interactions to create a highly geometrical specific interaction.
Use of dihedral building blocks whose internal symmetry favors planar assemblies.
As a first milestone, we show in vivo assembly of ordered arrays that are obtained by introducing a multicistronic vector carrying the genes of both proteins. Post lysis TEM characterization resolves the structure to 14 Angstrom, and pre-lysis optical characterization confirms the assembly takes place while proteins are expressed within the cells. As a second milestone we show in vitro assembly, which offers a controlled assembly environment that can be tuned, optimized, and applied to different practical purposes. We show that ordered micrometer scale arrays are robustly formed when the components are mixed in concentrations that are two orders of magnitude below those in which they are stably stored. Finally we show that multiple functional components can be either genetically fused or attached post-expression to the arrays, offering a direct route to introduce emerging, assembly-related, functionalities.
These recent achievements in the design, control, and optimization of the assembly process of complex protein 2D arrays, offers a new platform to generate biologically synthesized, synthetic materials, with custom designed functions beyond those found in nature.

**4:00 PM BM09.10.08**
**Kinetically Dependent M13 Bacteriophage-Based Self-Assembled Nanostructures for Dynamic Gap Plasmonics** Vasanthan Devaraj[1], JongMin Lee[1], Jiye Han[2], Kyounga Lim[1], Yeong Ju Lee[1] and Jin-Woo Oh[1, 2, 3]; [1]Research Center for Energy Convergence and Technology Division, Pusan National University, Busan, Korea (the Republic of); [2]Department of Nano Fusion Technology, Pusan National University, Busan, Korea (the Republic of); [3]Department of Nanoenergy Engineering, Pusan National University, Busan, Korea (the Republic of).

Significant progress on the fabrication of highly ordered and hierarchically organized nanostructures through self-assembly methods had received greater attention in recent years. One of the critical highlights in processing a fabrication using self-assembly was its ability to surpass the critical structural and functional complexity issues occurring with current bottom-up and top-down approaches. In this work, a bacterial virus – M13 bacteriophage (phage) is used to fabricate self-assembled nanostructures based on drop-cast fabrication technique. The employed drop-cast fabrication method is simple, straightforward and cost-effective and doesn't require any post-processing methods like etching or lithography to demonstrate (gap – tunable) plasmonic applications. Upon drop-casting M13 phage solution on the substrate, by exploiting natural evaporation kinetics at the meniscus, different distance-dependent nanostructures were formed in a single fabrication attempt: networking-like structure close to the center, bundled or single nanowire in the middle, and an island (or dot) close to sides. Reproducibility of these nanostructures was possible even when changing few fabrication parameters such as follows: when using different types of phages like wild-type, WHW-type, and metalized (silver- or gold- coated) M13 phages; depositing on different substrates like glass slide, silicon, and gold coated silicon. Size control of networking nanowires (diameter range ~ 10 nm – 150 nm) and islands (diameter range ~ 200 nm – 1000 nm) was possible by varying the concentration of M13 phages or with changes in humidity. Experimental plasmonic studies like scattering, absorption, electric field enhancement were carried out and verified by three-dimensional finite difference time domain simulations (3D FDTD). M13 phage-based nanostructures exhibited an excellent dynamic plasmonic properties using above-mentioned size control conditions. In that, mainly, it was possible to demonstrate a clear tunable gap based plasmonic scattering using humidity control. By varying the humidity, the gap between two nanowire structures or islands were either increased or decreased leading to dynamic changes in scattering resonances or in near-field enhancement. We hope our kinetically controlled self-assembled fabrication approach utilizing M13 phage will open exciting applications in the field of sensors, plasmonics, photonics, lithography-free fabrication of highly ordered nanostructures, and so on.

**4:15 PM BM09.10.09**
**Liquid Crystalline Behaviour of Surface Modified Laponite Clay Suspensions** Peicheng Xu; University of Cambridge, Cambridge, United Kingdom.

We present two new routes to surface modify either the negatively charged flat surfaces of Laponite discs with the comb-polymer, PLL-PEG (polylysine-polyethylen glycole) or the positively charged rims of these particles with the cucurbit[7]uril, CB[7], a barrel shaped molecule. We demonstrate that the PLL-PEG coating can completely suppress the ageing typically observed in aqueous Laponite solutions, thus allowing for the first time to access the dichotic liquid crystalline phases of these clays. We distinguish between three scenarios, insufficient coatings, perfect and excess coatings leading to different liquid crystalline textures. In the case of the functionalization with CB[7] we observe a very different evolution into the formation of lamellar sheets of laponite particles leading to a smectic like texture, with a large spacing bteween the lamellas caused by the long-ranged Coulomb repulsion between the negatively charged particles.

**4:30 PM BM09.10.10**
**Insights into the Interaction of Select Amino Acids with Anatase $TiO_2$ via DFT Calculations** Sai Phani Kumar Vangala and Parag A. Deshpande; Department of Chemical Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India.

Design of biocompatible materials with improved properties have found increasing attention due to the effective interaction of biomolecules with inorganic surfaces with their applications in implantology, biosensors and bioelectronics.[1-3] $TiO_2$ has been widely studied for this purpose as an inorganic support to adsorb single or multiple fragments of biomolecules due to its excellent biocompatibility, thermal stability and environmental friendly nature.[2-4] The present work focuses on the interaction of amino acid molecules such as arginine, cysteine and guanine over a nano-$TiO_2$ cluster using density functional theory (DFT) approach. Different configurations were explored for the adsorption of arginine, cysteine and guanine over the nano-$TiO_2$ cluster in order to find the best adsorption mode. Adsorption of these amino acids occured mainly via three functional groups, carboxyl (-COOH), amine ($NH_2$) and thiol (S-H) with the coordinated Ti-O groups. The energies of adsorption were -57.61 kcal/mol, -25.15 kcal/mol and -58.88 kcal/mol for the adsorption of arginine, cysteine and guanine on the $TiO_2$cluster. Computational FTIR spectra generated from the vibrational frequency analyses of the optimized structures further confirmed the adsorption of the amino acids on the surface of $TiO_2$ cluster. Density of states analyses was done for pristine and amino acids adsorbed $TiO_2$ to determine the gap between the valence band maximum (VBM) and conduction band minimum (CBM). The band gaps obtained were 3.25 eV, 2.95 eV, 3.09 eV and 2.83 eV for pure, arginine, cysteine and guanine adsorbed $TiO_2$. The band gap reduction phenomena of $TiO_2$ after adsoprtion with amino acids also confirmed the prominent adsorption of amino acids over the surface of $TiO_2$ cluster which enhanced the photoactivity of $TiO_2$ by shifting the optical adsorption towards visible light region posing another future application of $TiO_2$-amino acid complexes.

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**4:45 PM BM09.10.11**
**Coherent Nanoparticles within a Biogenic Single Crystal—A Biological Prestressing Strategy** Boaz Pokroy; Technion-Israel Institute of Technology, Haifa, Israel.

Materials in nature, in contrast to synthetic materials, are formed in ambient conditions and with a limited selection of elements. Nevertheless, nature reveals elegant strategies for achieving specific functions, ranging from skeletal support to mastication, from sensors and defensive tools to optical function. Here, utilizing state-of-the-art characterization techniques, we present yet another biostrategy, hitherto unidentified, for toughening the otherwise brittle calcite optical lenses found in the brittlestar *Ophiocoma wendtii*. This intriguing strategy employs coherent nanoprecipitates to induce compressive stresses on the host single crystal, functionally resembling the Guinier–Preston zones known in classical metallurgy. We believe that these calcitic nanoparticles, being rich in magnesium, segregate during or just after transformation from amorphous to crystalline phase, similarly to segregation behavior from a supersaturated quenched alloy.

Polishchuk I, Aronhime Bracha A, Bloch L, Levy D, Kozachkevich S, Etinger-Geller Y, Kauffmann Y, Burghammer M, Giacobbe C, Villanova J, Hendler G, Sun C Y, Giuffre A.J, Marcus M.A, Kundanati L, Zaslansky P, Pugno N.M, Gilbert Pupa U. P. A., Alex Katsman A and Pokroy B. Coherently aligned nanoparticles within a biogenic single crystal: A biological prestressing strategy. **Science**. 2017*;* **358:**1294

SESSION BM09.11: Poster Session III: Bionspired Materials
Thursday Afternoon, November 29, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

**BM09.11.02**
**Flow Imaging Technology for Evaluation of Polymer Microparticles—Analyzing Millions of Elastin-Like Polymer Coacervates One at a Time** Laura Marvin, James Vesenka, Wynter Paiva and Eva Rose M. Balog; Chemistry and Physics, University of New England, Biddeford, Maine, United States.

Biological and bioinspired polymer microparticles have broad biomedical and industrial applications, including drug delivery, tissue engineering, surface modification, environmental remediation, imaging, and sensing. Full realization of the potential of biopolymer microparticles will require methods for rigorous characterization of particle sizes, morphologies, and dynamics, so that researchers may correlate particle characteristics with synthesis methods and desired functions.

Toward this end, we evaluated biopolymer microparticles using dynamic imaging particle analysis, also known as flow imaging. This technology is becoming more widely used in the biopharmaceutical industry but is not yet well-known among the materials community. Our polymer, a genetically engineered elastin-like polypeptide (ELP), self-assembles into micron-scale coacervates.

We performed flow imaging of ELP coacervates using two different instruments, one with a lower size limit of approximately 2 microns, the other with a lower size limit of approximately 300 nanometers. We validated flow imaging results by comparison with dynamic light scattering and atomic force microscopy analyses. We explored the effects of various solvent conditions on ELP coacervate size, morphology, and behavior, such as the dispersion of single particles versus aggregates. We found that flow imaging is a superior tool for thorough and statistically powerful particle analysis of ELP coacervates in solution. We anticipate that researchers studying many types of microscale protein or polymer assemblies will be interested in flow imaging as a tool for rapid, quantitative, solution-based particle characterization.

**BM09.11.03**
**Bioinspired Assembly of Small Molecules in Cell Milieu** Zhaoqianqi Feng, Huaimin Wang and Bing Xu; Brandeis University, Waltham, Massachusetts, United States.

Self-assembly, the autonomous organization of components to form patterns or structures, is a prevalent process in nature at all scales. Particularly, biological systems offer remarkable examples of diverse structures (as well as building blocks) and processes resulting from self-assembly. The exploration of bioinspired assemblies not only allows for mimicking the structures of living systems, but it also leads to functions for applications in different fields that benefit humans. In the last several decades, efforts on understanding and controlling self-assembly of small molecules have produced a large library of candidates for developing the biomedical applications of assemblies of small molecules. Moreover, recent findings in biology have provided new insights on the assemblies of small molecules to modulate essential cellular processes (such as apoptosis). These observations indicate that the self-assembly of small molecules, as multifaceted entities and processes to interact with multiple proteins, can have profound biological impacts on cells. Here we illustrate that the generation of assemblies of small molecules in cell milieu with their interactions with multiple cellular proteins for regulating cellular processes can result in primary phenotypes, thus providing a fundamentally new molecular approach for controlling cell behavior.

**BM09.11.05**
**Enamel Proteins for Guided Mineral Growth** Karina M. Carneiro; Dentistry, University of Toronto, Toronto, Ontario, Canada.

Dental enamel is the outermost layer of teeth and is the hardest, most mineralized tissue in the human body. Its high crystallinity and hierarchical organization provide function and form the critical protective interface against external factors. Enamel formation involves a multi-step process guided by a complex mixture of proteins secreted by specialized cells. Key features of the underlying biomineralization mechanism remain unknown, primarily because the matrix is completely degraded during tissue formation. Amelogenin (AMEL) is the main protein present during enamel formation, with a suggested

role in acting as a scaffold for mineralization to occur. Amelotin (AMTN) is a recently discovered enamel matrix protein that is secreted in small amounts during tissue maturation. Previous studies have shown its role in enhancing mineralization *in vitro*. In this presentation, I will describe the hierarchical self-assembly of AMEL and AMTN, their functional relationship, and their individual and combined effects on calcium phosphate mineralization. Specifically, I will show evidence that AMTN promotes directional crystal growth on AMEL supramolecular structures under biomimetic conditions, suggesting a similar guided mineralization mechanism may occur *in vivo* during enamel formation.

**BM09.11.06**
**Chiral Tartaric Acid Can Selectively Regulate Brushite Bioceramic Crystallization** Hanan M. Moussa[1, 2], Wenge Jiange[1], Ammar Alsheghri[3], Alaa Mansour[1], Amir El Hadad[1, 4], Haihua Pan[5], Jun Song[3], Marc McKee[1] and Faleh Tamimi[1]; [1]Biomedical Science, McGill University, Montreal, Quebec, Canada; [2]Prosthodontics department, Benghazi University, Benghazi, Libya; [3]Department of Mining and Materials Engineering, McGill University, Montreal, Quebec, Canada; [4]Physics Department, Al-Azhar University, Montreal, Quebec, Canada; [5]Qiushi Academy for Advanced Studies, Zhejiang University, Zhejiang, China.

In natural biomineralized structures such as bone, teeth and nacre, remarkable mechanical properties result from the control of growth and organization of inorganic brittle crystals by specialized biomolecules (i.e. proteins); this interplay provides high-performance material strength and toughness. These biomolecules found in biominerals are homochiral, one of the most distinctive biochemical signatures of life, where they are composed exclusively of L-enantiomers of amino acids enriched in acidic carboxyl groups. Brushite bioceramics have been attracting great attention as a bone substitute material because they are biocompatible and resorbable under physiologic conditions. However, brushite bioceramics alone are brittle, and their mechanical properties are far inferior to bone.
We have discovered that brushite crystals have a chiral dynamic growth step susceptible for interaction with matching chiral molecules. Indeed, the growth of the chiral brushite step can be inhibited by stereochemical matching with the L-enantiomer of tartaric acid (L-(+)-Tar), hence inhibiting crystal precipitation and growth. Following on this discovery, here we also show that the simple addition of L-(+)-Tar can decrease the subunit crystal size of brushite bioceramics, and endow the bioceramic with high compressive strength and fracture toughness. In contrast, addition of the D-(-)-Tar enantiomer had an inverse negative affect on the mechanical properties, resulting in lower compressive strength and fracture toughness due to increased porosity. These observations are predicted by mathematical models that precisely described the inverse relationship of the mechanical properties with both subunit crystal size and total porosity content.
These findings provide insight into the role of chiral L-biomolecules in biomineralization, and they inform the rational for fabrication of bioceramics having controlled crystallographic structure and enhanced mechanical properties.

**BM09.11.07**
**Large Surface Plasmon Enhanced Fluorescence of Organic Dye Using M13 Virus-Based Framework and Its Application for *In Vitro* E.coli Detection** Shengnan Huang[1, 2], Jifa Qi[3, 2], Dane W. deQuilettes[4], Xiangnan Dang[5], Neelkanth M. Bardhan[3, 2] and Angela Belcher[1, 3, 2]; [1]Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [2]Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [3]Biological Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [4]Organic and Nanostructured Electronics Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [5]Eli Lilly and Company, Cambridge, Massachusetts, United States.

Fluorescence spectroscopy is a powerful tool for studying biological processes, but its applicability is often limited by the fluorophores, which should have high specific binding and emission efficiency. In this regard, M13 virus, a versatile biotemplate, has been used to assemble fluorophores on its viral capsid with molecular precision and to target various cells. Although the M13-fluorophore ensembles have high targeting specificity, these systems suffer from poor detection sensitivity due to low quantum yield of the fluorophores. To address these issues, we co-assemble cyanine 3 dye molecules and silver nanoparticles on the M13 virus to create a fluorescent probe capable of high binding specificity and high fluorescence efficiency. Fluorescence enhancement is achieved though precisely tuning the nanoparticle size and the distance between the dye molecules and nanoparticles. We achieve up to 24-fold enhancement of cyanine 3 fluorescence, enabling *in vitro* detection of E. coli with improved sensitivity than the control probes without silver nanoparticles. These results demonstrate an inexpensive, room-temperature framework for achieving tuned fluorescence enhancements. We expect the methodology developed in this work to be amendable to a wide range of fluorescence-based imaging and detection of tumors and bacterial infections.

**BM09.11.08**
**Fabrication and Self-Assembly of Hierarchical Nanostructures** Moha M. Shahjamali and Vinothan N. Manoharan; School of Engineering and Applied Science, Harvard University, Cambridge, Massachusetts, United States.

In Nature, hierarchical structures such as arrays of pillars are source of various functionalities and have inspired broad applications in surface engineering, heat/electron transfer and sensing. However, traditional top-down fabrication approaches suffers from low control over their aspect ratio, tilt angle, lattice arrangement and flexibility.
To address such limitations, we demonstrate a new, simple method to fabricate arbitrary arrangements of flexible high-aspect-ratio nanopillars using a combination of two-photon lithography and oxygen plasma etching. We show that the method can create millimeter-size arrays of nanopillars with tunable dimensions, cross-sections, bending stiffnesses, tilt angles and aspect ratios. In particular, we demonstrate aspect ratios up to 500, more than 15 times larger than has been shown in other fabrication methods such as replica molding, photolithography and e-beam lithography. We also show that high-aspect-ratio nanopillars assemble into chiral twists through kinetically controlled evaporation.

SESSION BM09.12: Peptoid and Other Biomimetic Polymers
Session Chairs: Chun-Long Chen and Tiffany Walsh
Friday Morning, November 30, 2018
Hynes, Level 2, Room 205

**8:30 AM *BM09.12.01**
**Universal Backbone Conformation in Peptoid Polymer Assemblies** Sunting Xuan, Doug Greer, Nitash Balsara and Ronald N. Zuckermann; Lawrence Berkeley National Lab, Berkeley, California, United States.

How do polymer crystals differ from small molecule crystals? With the recent advent of sequence-defined peptoid polymer chemistry, we can now readily

synthesize molecularly pure, peptoid polymers, with precision, atomic control of their molecular structure. This allows us to systematically explore how the chemical structure of a polymer chain effects its ability to crystallize and pack into well-defined assemblies. It allows us to explore the impact of main chain length and side chain shape on molecular crystallization. Here we used X-ray scattering and cryo-TEM to examine a series of crystalline, sequence-defined peptoid diblock copolymers, where we varied the main chain length, side chain chemistry and size, terminal groups and monomer composition. The peptoids assemble into both 2D and 3D lattices, depending on solvent conditions, allowing a variety of characterization tools to be used to elucidate the molecular structure and packing configuration. Interestingly we found that in over 22 crystalline peptoid polymers reported in the literature, all of them likely share a similar packing motif, where the chains are extended, and the backbones are in an all-cis conformation. This common structural motif over a wide variety of structures, suggests favorable backbone-backbone interactions resulting in chain alignment, and provides great opportunities to engineer these crystals by using synthesis to introduce point mutations to introduce specific function.

**9:00 AM BM09.12.03**
**The Controlled Self-Assembly of Fluorescent Block Copolymers Driven by π-π Interaction** Feng He; Department of Chemistry, Southern University of Science and Technology, Shenzhen, China.

In recent years, block copolymers have attracted much attention for they can be used as building blocks to fabricate 1/2D nano-/micro- architecture driven by crystallization, electrostatic interaction and crosslinking. *We combine conjugated fluorescent block poly (phenylene vinylene) (PPV) and poly (2-vinyl pyridine) (P2VP) to build rod-coil type diblock copolymer PPV-P2VP with strong fluorescence and self-assembly property. Nano-/micro- supramolecular fluorescent architectures of the copolymers were obtained by dissolving- cooling-aging process. The obtained structures could be transformed from one-dimensional (ribbons) to two-dimensional (square micelles) by changing the alkyl side chains of PPV blocks, and the scale of the structures could by controlled by changing the block length ratio of PPV and P2VP in the copolymer. The self-assembled morphology of the low block ratio exhibits a significant concentration dependence, and the concentration dependence disappears as the block ratio increases. The morphological characterization and kinetic studies of the formed nano-/micro- architectures show that the conjugated forces play an important role in self assembling process.*
**Reference：**
Lang Han, Meijing Wang, Xiangmeng Jia, Wei Chen, Hujun Qian and **Feng He***, "Uniform two-dimensional square assemblies from conjugated block copolymers driven by π–π interactions with controllable sizes", **Nat. Commun.**, *2018*, 9, 865-876.

**9:15 AM BM09.12.04**
**Plant Tissue Morphogenesis-Inspired Molecular Self-Assembly of Complex Three-Dimensional Structures in Soft Materials** Changjin Huang[1], David Quinn[1], Subra Suresh[2] and K. Jimmy Hsia[1]; [1]Carnegie Mellon University, Pittsburgh, Pennsylvania, United States; [2]Nanyang Technological University, Singapore, Singapore.

Many applications in tissue engineering, flexible electronics, and soft robotics call for approaches that are capable of producing complex three-dimensional (3D) architectures in soft materials. Uncovering the principles that biological systems utilize to develop complex 3D shapes and patterns (i.e. morphogenesis) is a promising route. Although the general principles dictating how differential cell growth leads to the formation of 3D shapes in plant tissue morphogenesis have been identified, an *in vitro* system that can closely mimic the process of tissue growth and morphogenesis is still missing. In this work, we use polyacrylamide hydrogel as a model system to mimic plant tissue growth. Our strategy takes advantage of the detrimental effect of polymerization inhibitors (i.e. oxygen) by turning it into an effective way to manipulate hydrogel formation. We demonstrate that the polymerization of polyacrylamide hydrogel is able to faithfully resemble all the essential features of plant tissue growth and morphogenesis. During polymerization, the oxygen plays a role mechanistically similar to the role of growth factors in tissue growth, and the continuous growth of hydrogel enabled by diffusion of monomers/cross-linkers into the porous hydrogel is similar to the mechanisms of tissue growth enabled by nutrient transport through vascular networks. The cross-linked hydrogel structure enabled by covalent bonds resembles the concept of interconnected cell walls in plant tissues. Similar to the differential growth in plant tissues facilitated by non-uniformly distributed growth factors and/or different growth rates among different constituent parts, accumulated residual stress as a result of differential polymerization of hydrogel leads to the formation of 3D structures. Our technique opens up new avenues to studying many growth phenomena found in nature and generating complex 3D structures to benefit diverse applications.

**9:30 AM BREAK**

**10:00 AM BM09.12.05**
**Functional Uniform and Patchy Two-Dimensional Assemblies by Living Crystallization-Driven Self-Assembly** Samuel Pearce[2, 1] and Ian Manners[1]; [1]School of Chemistry, University of Bristol, Bristol, United Kingdom; [2]Bristol Centre for Functional Nanomaterials, University of Bristol, Bristol, United Kingdom.

Two-dimensional (2D) nanostructures, typified by graphene or metal dichalcogenide nanosheets, are of interest in a broad range of applications including optoelectronics and photovoltaics. Solution-phase block copolymer (BCP) self-assembly is a widely-studied method to produce nanostructures using soft materials, although examples of dimension control using such methods are rare. Crystalline-coil BCPs can undergo living crystallization-driven self-assembly (CDSA), resulting in BCP micelles of controlled size and low polydispersity. Furthermore, length control over amphiphilic 1D BCP micelles have allowed access to complex superstructures, such as "windmill" supermicelles and large micelle superlattices. Recently we have extended living CDSA to the formation of 2D structures, through seeded-growth of BCP/homopolymer blends[1] and charge-terminated crystallizable homopolymers.[2] Various 2D platelet morphologies of controllable area and aspect ratio are now accessible. These methods can be applied to biocompatible or optoelectronic crystalline polymers, providing materials with potential application in nanomedicine or nanoelectronics.[3,4]

**References**
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(2) He, X.; Hsiao, M.-S.; Boott, C. E.; Harniman, R. L.; Nazemi, A.; Li, X.; Winnik, M. A.; Manners, I. Two-Dimensional Assemblies from Crystallizable Homopolymers with Charged Termini. *Nat. Mater.* **2017**, 16, 481.
(3) He, X.; He, Y.; Hsiao, M.-S.; Harniman, R. L.; Pearce, S.; Winnik, M. A.; Manners, I. Complex and Hierarchical 2D Assemblies via Crystallization-Driven Self-Assembly of Poly( L -Lactide) Homopolymers with Charged Termini. *J. Am. Chem. Soc.* **2017**, *139*, 9221.
(4) Jin, X.-H.; Price, M. B.; Finnegan, J. R.; Boott, C. E.; Richter, J. M.; Rao, A.; Menke, S. M.; Friend, R. H.; Whittell, G. R.; Manners, I. Long-Range Exciton Transport in Conjugated Polymer Nanofibers Prepared by Seeded Growth. *Science,* **2018**, *360*, 897

**10:15 AM BM09.12.06**
**Tuning Unit Cell Type and Size of Block-Copolymer Nanostructures by Lipid Hybridization** Cecilia Leal, Minjee Kang, Yookyung Go and Marilyn Porras-Gomez; University of Illinois, Urbana-Champaign, Urbana, Illinois, United States.

Block-copolymers self-assemble into a myriad of fascinating structures. These systems have been instrumental to direct the organization of superstructures of many types of inorganic materials spanning bio-minerals, semiconductors, and even superconductor materials. The traditional approach to stabilize nanostructures of block-copolymers is tuning the chemistry and/or volume fraction of the blocks. In this presentation, we will show that a single block-copolymer type that *per se* is only stable in 1D multilayers can organize into multiple nanostructures, when physically hybridized by a lipid template. Polymer-lipid physical hybrids adopt tunable and remarkably well-ordered 1D lamellar, 2D hexagonal, and 3D bicontinuous cubic structures in air. Importantly, the unit cell sizes are one order of magnitude smaller than attained with pure block-copolymer systems allowing superior packing density of inorganic materials.

**10:30 AM BM09.12.07**
**Copolymer-Stabilized Coacervate Microdroplets as Multicompartmentalized Artificial Cells** Alex Mason[1], Loai Abdelmohsen[1], N. Amy Yewdall[1], Bastiaan Buddingh[1], David Williams[2] and Jan van Hest[1]; [1]Technische Universiteit Eindhoven, Eindhoven, Netherlands; [2]Chemistry, Swansea University, Swansea, United Kingdom.

Complex coacervates are a membrane-free, solution-phase material that are formed by the electrostatic interactions between oppositely-charged macromolecules. They are interesting from an artificial cell perspective because they resemble the cell cytosol, particularly as a crowded and charged environment. However, due to their inherently membrane-free nature, they are unstable, with coacervate droplets prone to coalescence on relatively short time scales, which inhibits their use in longer experiments. This work describes the development of a triblock copolymer that self-assembles on the surface of an amylose-based complex coacervate, forming a robust, passivating layer that prevents droplet coalescence and content mixing. These discrete, cell-sized, polymer-stabilized coacervate droplets are capable of encapsulating macromolecular cargo, which remain in an active conformation. In addition, the polymer membrane is semi-permeable, enabling the incorporation of a simple enzymatic cascade in different protocell populations, a rudimentary demonstration of protocellular communication.

This robust scaffold has now been utilized to demonstrate the formation of a multicompartment system. Through the encapsulation within the coacervate protocell of nanometre-sized polymer vesicles containing functional enzymes, it is possible to generate assemblies reminiscent of organelles within a eukaryotic cell. This structural motif was used to incorporate enzymatic cascades, demonstrating increased rates of reaction and control over the reaction pathway depending on the spatial organization of enzymes within the artificial organelles. These polymer-stabilized coacervate droplets already offer many characteristics that are interesting to the artificial cell community, while also being modular and open to further polymer engineering, paving the way for the incorporation of more complex biomimetic systems and behaviours.

**10:45 AM BM09.12.08**
**Redox-Responsive Disassembly of Dual Diselenide Containing Triblock Copolymer Nanocarriers Based on Poly(ethylene glycol)-b-PCL-b-poly(ethylene glycol) for Triggered Anticancer Drug Release** Balkew Z. Hailemeskel, Kefyalew Dagnew Addisu, Abegaz T. Andrgie, Hsiao-Ying Chou and Hsieh Chih Tsai1; Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology (NTUST), Taipei, Taiwan.

In recent years, different kinds of nanoparticles (NPs) have been synthesized with the aim of being utilized as drug delivery system for anticancer drugs. In this study, diselenide containing biodegradable triblock copolymer, poly(ethylene glycol)-b-poly(caprolactone)-b-poly(ethylene glycol) (mPEG-$SeSe)_2$PCL was carefully prepared through the reaction of ditosylated polycaprolactone and poly(ethylene glycol) methyl ether tosylate in the presence of disodium diselenide. The diselenide containing triblock copolymer allowed the formation of selfassembled aggregates which revealed response to glutathione (GSH) and Hydrogen peroxide ($H_2O_2$) because of the redox-stimuli cleavable property of diselenide bond. Such redox response confirmed an increased release of Dox from the nanoparticles in tumor microenvironments. The cytotoxicity of $(mPEGSeSe)_2$PCL triblock copolymer was tested by cell viability assay using HeLa and HaCaT cells. The in vitro drug release studies exhibited that above 62 % and 56 % of Dox was released in 72 h at 37$^{o}$C from the nanoparticles in the presence of 6.5 mM GSH and 0.1% $H_2O_2$ respectively, whereas only about 30 % of Dox was released from the nanoparticles without stimuli under the same conditions. The MTT assay studied using HeLa cells and HaCaT cells showed that the Dox-loaded $(mPEGSeSe)_2$PCL nanoparticles have high antitumor activity in HeLa cells and low antitumor activity in HaCaT within 24h incubation. Furthermore, the confocal laser scanning microscopy (CLSM) measurements confirmed that the Dox-loaded nanoparticles could be localized efficiently by HeLa cells and release Dox inside the tumor cells. However, the internalization of Dox-loaded nanoparticles and release of Dox inside HaCaT cells was very less. The results indicated that the synthesized material $(mPEGSeSe)_2$PCL was biocompatible and it could be an alternative candidate for anticancer drug delivery system.

**11:00 AM BM09.12.09**
**Highly-Crystalline Peptoid-Based Nanomaterials Assembled from Short Peptoid Oligomers** Peng Mu[2, 1], Guangwen Zhou[2] and Chun-Long Chen[1]; [1]Pacific Northwest National Laboratory, Richland, Washington, United States; [2]Mechanical Engineering, Binghamton University, The State University of New York, Binghamton, New York, United States.

Peptoid (N-substituted glycines), as one of the unique sequence-defined synthetic “foldamers that mimic proteins and peptides for functions, - have recently received increasing attention for building biomimetic nanomaterials with hierarchical structures. Due to the unique proteinase-resistance, chemical and thermal stabilities of the peptoids, peptoid-based nanomaterials are promising for applications under the hostile environment where protein- or peptide-based materials are vulnerable and easy to degrade or lose functions. Recently, by designing amphiphilic oligomers that contain aromatic hydrophobic domains, our group recently reported their self-assembly into highly crystalline membrane-mimetic 2D nanomaterials and 1D nanotubes. We demonstrated that these peptoid-based nanomaterials are highly stable and a wide range of functional groups can be precisely placed within these materials as peptoid side chains. Furthermore, our mechanistic studies indicate that the packing of hydrophobic side chains is the key for the stabilization of these biomimetic nanomaterials. To gain the atomic level of understanding the self-assembly of these 2D and 1D nanomaterials, herein, we report the design and synthesis of short peptoid oligomers for self-assembly of biomimetic nanomaterials with similar structures. X-ray diffraction data indicate that nanomaterials assembled from these short sequences are highly crystalline and the change of one side-chain group at the N-terminal can significantly influence the materials formation process. By analyzing the XRD data of a number of biomimetic materials assembled from peptoids with similar chemistries, and the assistance of CryoEM and AFM characterizations, we gained a better understanding of peptoid assembly process and the structures of 2D and 1D peptoid-based nanomaterials.

**11:15 AM BM09.12.10**
**Self-Assembly and Supramolecular Chirality Reversal of a Sophorolipid-Functionalized Chromophore** Kyle C. Peters[1], Shekar Mekala[2], George Heidbreder[1], Richard A. Gross[2] and Kenneth Singer[1]; [1]Physics, Case Western Reserve University, Cleveland, Ohio, United States; [2]Center for Biotechnology and Interdisciplinary Studies, Rensselaer Polytechnic Institute, Troy, New York, United States.

Bio-based, self-organizing molecules are of considerable interest as functional materials due to their structural versatility, mildly-sustainable bio-synthesis, and sophisticated nano-architectures that introduce chirality. This work is focused on molecules designed to exploit the light-absorbing and macromolecular self-assembly abilities of Nature for potential applications as functional organic materials. Among these potential candidates, photoactive chromophores show promise for providing (opto)electronic and highly tunable structure and morphology. Additionally, a distinct class of microbially produced glycolipid biosurfactants, known as sophorolipids, show promise for providing the driving mechanism for self-assembly through carbohydrate hydrogen bonding. Herein, we explore the self-assembly and optical properties of a novel series of sophorolipid-functionalized zinc porphyrin molecular geometries that provide an intricate interplay among steric, pi-pi and hydrogen bonding interactions. We have investigated the delicate interplay of these non-covalent self-organizing interactions and their influence on multi-chromophoric aggregation by precise structural modification of the sophorolipid's hydrogen bonding moiety and steric interactions through hydrocarbon chain modulation. Spectroscopic studies reveal solvent-promoted self-assembly in dilute methanol/water solution. It was found that helical supramolecular structures form by strong carbohydrate hydrogen bonding interactions, in contrast to nanosphere formation with acetyl-group substitution that eliminates hydrogen bonding interactions. Temperature-dependent UV/vis absorption and circular dichroism show that helical supramolecular polymerization proceeds through a cooperative mechanism of self-assembly for compounds that contain free hydroxyl groups capable of hydrogen bonding interactions. Further, it was discovered that shortening of the sophorolipid hydrocarbon chain promotes helical reversal accompanied with a large increase in the cooperative nature of assembled structures.

**11:30 AM BM09.12.11**
**Anti Fatigue-Fracture Hydrogels by Forming Percolated Crystal Domains** Shaoting Lin, Hyunwoo Yuk, Ji Liu, Xinyue Liu, Hyun C. Loh, Admir Masic and Xuanhe Zhao; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Natural materials in human body (e.g. heart valves, cartilages and muscles) can undergo millions of cycles without losing their functionality. However, synthetic hydrogels including recent developed tough hydrogels are susceptible to fatigue-fracture even under a few thousands of cycles. To date, there are no unraveled mechanisms proposed yet to design anti fatigue-fracture hydrogels, which limits synthetic hydrogels' applications that require long-term robust performance. Here, we report a biomimetic strategy to design anti fatigue-fracture hydrogels via controlled crystal domains. The strategy is to form percolated crystal networks in semi-crystalline hydrogels, retarding crack initiation under cyclic loading owing to high-strength crystal. To validate the proposed strategy, we use the poly(vinyl alcohol) (PVA) hydrogel as an exemplar material system and adopt a new experimental method to measure the fatigue threshold of the semi-crystalline networks with controlled crystal morphology. We show that the critical fracture energy for fatigue-fracture (i.e. fatigue threshold) can increase up to 1000 $J/m^2$ as the crystallinity in semi-crystalline network reaches the percolation threshold, higher than that of existing reported hydrogels in the order of 1-100 $J/m^2$. Following the design strategy, we further demonstrate two approaches to improve long-term mechanical performance: enhancing fatigue threshold via inducing local crystal domains around crack tip and achieving long-term high strength with crystal reinforcement.

**11:45 AM BM09.12.12**
**Small Angle Neutron Scattering Analysis of Gold Induced Gel Formation of Chitosan** Radha Perumal Ramasamy[1] and Vinod K. Aswal[2]; [1]Department of Applied Science and Technology, ACT Campus, Anna University, Chennai, India; [2]Solid State Physics Division, Bhabha Atomic Research Centre, Mumbai, India.

Biopolymers are studied extensively due to its wide applications in the field of bio-technology, micro fluidics and lab on chip devices. Chitosan is natural biopolymer derived from chitin. It has wide applications in bio-medical engineering because of its biocompatibility and biodegradability. Also, chitosan act as reducing and stabilizing agent for the metal ions. Chitosan is also a good candidate in batteries as membranes. It is therefore important to study the conformational changes of chitosan. Understanding the conformational changes in chitosan will help us better understand the microstructural modifications taking place inside membrane made using chitosan. In this research work, SANS was used to understand the modifications in the radius of gyration (Rg) values of chitosan in (i) solution, (ii) in presence of $HAuCl_4$ and (iii) in presence of $LiClO_4$. Small Angle Neutron Scattering is a useful technique for the characterization of biological materials. SANS experiments involve scattering of a monochromatic neutron beam from the sample and measures the scattered neutron intensity as a function of scattering vector. The wavelength of the neutron beam used was 5.2 Å with a resolution ($\Delta\lambda/\lambda$) of about 15%. All of the data were collected in the accessible Q range of 0.017–0.35 $Å^{-1}$. All of the SANS data were corrected for the background, the empty cell contribution, and solvent contribution, and were normalized using standard procedure. Chitosan solution was prepared by adding 1% (w/v) of chitosan powder, 1.5% (w/v) of acetic acid to $D_2O$. When $HAuCl_4$ was added to chitosan solution, higher concentrations of $HAuCl_4$ (more than 3mM) gave rise to gels. When chitosan solution was dried in a dish it gave rise to films. SANS shows that the chitosan solution (liquid) had greater Rg value than the chitosan film. For chitosan-gold gels the Rg value did not change in gels from that of solution. There was no correlation length for the fitting for chitosan in solution, however there was correlation length observed in the gels. This indicates that in gels the chitosan units are more localized than in solution phase. To chitosan solutions and chitosan-gold gels LiClO4 was also added. The films formed by solution casting chitosan-$LiClO_4$ solution and gels formed using Chitosan-3mM $HAuCl_4$- $LiClO_4$ were also analyzed using SANS. The Interestingly, chitosan-Au-Li film shows the formation of star like structures which are not observed in case of gels. The correlation length for Chitosan-3mM $HAuCl_4$- $LiClO_4$ was lesser than that of Chitosan-3mM $HAuCl_4$ gels while the Rg was nearly the same for both Chitosan-3mM $HAuCl_4$-$LiClO_4$ and Chitosan-3mM $HAuCl_4$ gels Hence we conclude that $HAuCl_4$ can localize chitosan units in solution leading to formation of gels and the incorporation of LiClO4 in chitosan-gold gels can make the correlation length smaller and thereby affect the gels mechanical properties.

SESSION BM09.13: Applications of Bioinspired Materials
Session Chairs: Chun-Long Chen and Shuguang Zhang
Friday Afternoon, November 30, 2018
Hynes, Level 2, Room 205

**1:30 PM *BM09.13.01**
**Design of Bioinspired Peptide-Based Functional Coatings** Meital Reches; Hebrew University, Jerusalem, Israel.

Changing the chemical and physical properties of a surface is important for many fields. This includes the design of new medical devices, antifouling materials and smart surfaces. Surface chemistry and topography determine the interactions of biomolecules with an implant and therefore govern its fate in the body. It also controls the interactions of surfaces with other biological entities such as bacteria and cells that lead to the undesirable process of biofouling.
This lecture will present a new platform for the formation of functional coatings. The coating is based on simple peptides that self-assemble into a layer on various surfaces. The functionality of the coating is controlled by the sequence of amino acids of the peptide. This peptide-based coating can resist biofilm

formation and direct cell attachment. It could be useful in hospitals to prevent health-associated infections, in water desalination facilities to arrest membrane blockage by biofouling and in the design of implants.

**2:00 PM BM09.13.02**
**Aerosol-Assembled Re-Entrant Textures for Superamphiphobic Coatings and Devices** William S. Wong[1], Zuankai Wang[2], Antonio Tricoli[3] and Vincent Craig[4]; [1]Physics at Interfaces, Max Planck Institute for Polymer Research, Mainz, Germany; [2]Department of Mechanical and Biomedical Engineering, City University of Hong Kong, Hong Kong, China; [3]Research School of Engineering, The Australian National University, Canberra, Australian Capital Territory, Australia; [4]Applied Mathematics, The Australian National University, Canberra, Australian Capital Territory, Australia.

Top-down fabricated re-entrant profiles are ubiquitous in the field of superamphiphobicity. However, their complex geometrical design and poor scalability presents significant challenges. Alternatively, bottom-up assembled superamphiphobic surfaces do exist, but true evidence of re-entrancy is, to our knowledge, never demonstrated. Inspired by these limitations, we propose the use of aerosol-assembly for achieving stochastic agglomerate textures with distinct and potentially tunable re-entrant profiles. Modifications to deposition parameters enabled a transitional-shift from quasi-pillar shaped geometries to quasi-inverted trapezoidal configurations. For the first time, re-entrancy and stochastically developed superamphiphobicity were correlated, validated using experimental wetting and computationally simulated particle assembly. Coatings developed were superamphiphobic-functional, preserving the Cassie-Baxter state (CA > 150°, SA < 10°) with fluids down to surface tensions of ca. 25 mN/m.[1] Owing to the dimensional- and geometry- independent self-assembly, this technique is capable of producing functional coatings on highly complicated substrate profiles, even within fine needle capillaries. To this end, a series of contamination-proof, contact-free micro(fluid)mechanical devices were fabricated. They culminated in the unprecedented demonstration of producing and manipulating nano-liter droplets from ultra-low surface tension fluids.[2,3] We hope that our findings could take root within and beyond the field of functional superdewettability, advancing progress in emerging fields such as high-resolution 3D printing, tissue- and biomedical engineering.

**References**
1. Wong, W. S. Y. et al. *ACS Nano* **2016**, *11*, 587–596.
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**2:15 PM BM09.13.03**
**Understanding the Impact of Ligand Composition on Protein Corona Formation around Au Nanoparticles** Sam Hoff[1], Desiré Di Silvio[2], Sergio Moya[2], Ronald Ziolo[3] and Hendrik Heinz[1]; [1]University of Colorado Boulder, Boulder, Colorado, United States; [2]Soft Matter Nanotechnology Group, CIC biomaGUNE, San Sebastian, Spain; [3]Centro de Investigación en Química Aplicada, Saltillo, Mexico.

The makeup of coatings on nanoparticles in biological systems has an important impact on the fate and stability in cells and tissues. Ligands attached to nanoparticles, as well as protein coronas which form around nanoparticles in physiological environments, can be altered to change the destination of the nanoparticles, the time in the blood stream, and potential therapeutic functions. In this study, molecular dynamics is employed to study how the chemistry of end groups and length of ligands attached to gold nanoparticles affects the accessible surface structure. The structure and end groups have a marked change on the binding ability and binding conformation of Bovine Serum Albumin and Concanavalin A. PEGylated chains ending in a butanamide present a much smoother surface structure on the nanoparticle compared to that of PEGylated ligands ending in glucosamine which forms a rough surface capable of forming many weak unspecific non-covalent bonds. We use the CHARMM27 -Interface force field which yields interfacial properties directly comparable to measurements. The study is being driven by experimental results and is expected to give insight into how protein - ligand interactions work, as well as an advanced understanding of ligand conformations, opening doors to designing ligands with the purpose of forming specific protein coronas to control the destination of nanoparticles for therapeutic activity.

**2:30 PM BREAK**

**3:00 PM BM09.13.04**
**Manganese Loaded PH Stimuli-Responsive Polymer-Metal Complex Nanomaterials with High Magnetic Resonance Imaging for Tumor Imaging** Kefyalew Dagnew Addisu and Hsieh Chih Tsai1; Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology (NTUST), Taipei, Taiwan.

The development of nontoxic and biocompatible contrast agents (CAs) create new opportunities for potential applications in clinical magnetic resonance imaging (MRI) diagnosis. Manganese-based nanoparticles (NPs) are an emerging new class of MRI CAs that provide impressive contrast abilities with its low immunotoxicity property. Herein, PEGylated $Mn^{2+}$-chelated Alginate-polydopamine materials (NPs) (PEG-AlgPDA(Ca/Mn) were successfully developed with strong brighter MRI signals with r1=12.54 $mM^{-1}$ $s^{-1}$ in 7.0 T MRI images, based on the use of $Mn^{2+}$ ions as CAs and alginate-polydopamine as a biogenic polymer. The lower pH (5-6) tumor environment promote $Mn^{2+}$- release from alginate- polydopamine complex to enhance tumor $T_1$ _ relaxivity effect. The obtained AlgPDA(Ca/Mn) NPs exhibited significant MRI signal improvement both in *in-vitro* and *in- vivo* imaging. Moreover, the excellent AlgPDA(Ca/Mn) NPs biocompatibility was confirmed by a standard MTT assay and Haemotoxylin and Eosin (H&E) staining. Therefore, the developed AlgPDA(Ca/Mn) NPs could provide a new insight for bioresponsive noninvasive tumor detection and comprehensive anatomical diagnosis of cancer cells.
KEYWORDS: Nanostructured materials, Magnetic Resonance Imaging, Polydopamine, Manganese

**3:15 PM BM09.13.05**
**A General Physical Confinement-Based Approach to Semiconductor/Plasmonic Nanoparticle Composites** Abby Goldman[1], Jeffrey X. Zheng[1], Emily Asenath-Smith[2] and Lara A. Estroff[1, 3]; [1]Department of Materials Science and Engineering, Cornell University, Ithaca, New York, United States; [2]Cold Regions Research and Engineering Laboratory (CRREL), US Army Engineer Research and Development Center (ERDC), Hanover, New Hampshire, United States; [3]Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, New York, United States.

Plasmonic nanoparticle/semiconductor composites hold promise for optoelectronic applications ranging from solar cells to photocatalysts. There are two typical morphologies for such heterostructures, core-shell nanoparticles and pre-formed semiconductor nanostructures that are decorated with nanoparticles, but both have significant limitations on the degree to which the absorption and charge transfer can be enhanced. A composite architecture in which multiple nanoparticles can be incorporated into a crystalline rod without the insulating barriers associated with ligands could allow us to further enhance optoelectronic performance. Biomineralization routinely creates composite crystals, where second phases are incorporated within single crystalline domains, thereby imparting improved functionality to the composite compared to a pure single crystal. Organisms use a combination of strategies (chemical and physical) to form these composites. Here, we focus on the bio-inspired growth strategy of crystallization in physical confinement as a means to create composite plasmonic nanoparticle/semiconductor nanostructures. Our group previously showed that track-etched membranes could be used as a

template for the formation of composite $Cu_2O$/Au nanoparticle rods, where a large number of Au nanoparticles are encapsulated within crystalline cuprite nanorods (Chem. Mater. 2017). In this work, we show the generalizability of this physical confinement-based approach to create other semiconductor/nanoparticle composites, such as $Cu_2O$/Ag and ZnO/Au. First, we load the track etched membrane with nanoparticles of an appropriate diameter with respect to the diameter of the pores such that the nanoparticles jam within the pores of the membrane. Then, using low-temperature, aqueous growth methods, we grow metal oxide semiconductors, which grow into the membrane pores and encapsulate the nanoparticles. By incorporating collections of nanoparticles into crystalline rods, we access a relatively unexplored morphology of plasmonic nanoparticle/semiconductor heterostructure that we predict may have enhanced light collection and charge separation compared to the current typical morphologies.

**3:30 PM BM09.13.06**
**Interaction Between Target Membrane Proteins and Ligand-Decorated Polymeric Micelles Penetrating Blood-Brain Barrier** Noriko Nakamura[1, 2], Yasutaka Anraku[1, 2], Shigeto Fukushima[2], Kazuko Tou[2], Horacio Cabral[1, 2] and Kazunori Kataoka[1, 2]; [1]The University of Tokyo, Tokyo, Japan; [2]Innovation Center of NanoMedicine, Kanagawa, Japan.

Precisely programmed block copolymers self-assembly nano-structures such as micelles, vesicles and nanotubes in aqueous solution, have attracted increasing interests from all over the world as the biomaterial which has potential mainly for medical applications. Most typical example is the polymeric micelles with distinctive core-shell architecture, have great potential as drug delivery systems (DDS) to cancer and other intractable diseases. Hydrophilic shell provides polymeric micelles with stealth effect against foreign body recognition system in the body, while inner core works as a nano-reservoir of various cargo compounds. The polymeric micelle provides a promising system for delivery of therapeutic or diagnostic agents to diseased parts of the body, particularly solid cancers which have blood vessels with enhanced permeability, and some clinical trials are currently in progress. Meanwhile, designing a polymeric micelle that transports nucleic acid-based drugs such as siRNA, mRNA and pDNA have great potential for the therapy of central nervous system (CNS) disorders, through the barrier of a normal blood vessel with unenhanced permeability remains a challenging task. For the development of DDS to the CNS, blood brain barrier (BBB) is the obstacle, which excludes most drugs with the tight junction between brain capillary endothelial cells (BCECs). Recently our group developed glucose decorated polymeric micelles (Gluc/m) targeting glucose transporter 1 (GLUT1). GLUT1 is highly expressed on the BCECs and its localization can be manipulated by controlling the blood glucose level. Optimizing glucose ligand density on the surface of Gluc/m and glycemic control, Gluc/m achieved 6 %dose/g accumulation in the brain and attained its BBB penetrating ability. Although glucose-decorated micelles with short length PEG chains (2 kDa) can be recognized by GLUT1 and observed accumulating in brain, micelles with long length PEG chains (12 kDa) cannot recognize GLUT1. For increasing stability of micelles and loading various drugs, the development of ligand-loaded micelles with high molecular weight PEGs which maintains the ligand accessibility is needed. Previous research hypothesized that the ligand mobility is restrained by the neighboring PEG chains and the accessibility of ligands to the receptor is reduced when longer ligand-installed PEG chains attached to nanoparticles.
In this research, for the purpose of overcoming PEG dilemma, the novel polymeric micelle consisting of long PEG conjugated to the glucose ligand molecule and short PEG was developed. This technique is called cocktail PEGylation, and mixing short PEG is expected to increase the mobility of ligand molecules. The interaction between GLUT1 and cocktail PEGylated Gluc/m was estimated *in vitro* and *in vivo*. The brain accumulation of Gluc/m with long PEG was dramatically improved by cocktail PEGylation.

**3:45 PM BM09.13.07**
**Nitric Oxide-Responsive Nanogel for Treating Rheumatoid Arthritis** Jiwon Yeo, Yeong Mi Lee and Won Jong Kim; POSTECH, Pohang, Korea (the Republic of).

Nitric oxide (NO) is a physiological molecule that plays a key role in our body such as, vasodilation and inflammation. In respect of inflammation, NO is known to be related with RA which is a chronic inflammatory autoimmune disease that involves the joints. NO from abnormal macrophage upregulates osteoclasts to destroy a cartilage and recruits other immune cells inducing inflammation. In our group, we already reported NO-responsive macro-sized hydrogel by synthesizing NO-cleavable crosslinker. Herein, we further investigate NO-responsive nanogel for treating RA. The abnormal macrophage in the RA lesion secretes much higher concentration of NO compared with normal one. Thus, we designed NO-responsive nanogel that removes NO in abnormal joint and then alleviates a progress of RA. We represented the formation of the nanogel using acrylamide and NO-cleavable linker and showed its swelling behavior responding to NO through transmission electron microscopy (TEM) and dynamic light scattering (DLS). We also confirmed higher NO capturing efficiency of NO-cleavable crosslinker than N, N'-methylene bis-acrylamide via griess assay. For in vivo study, we prepared a collagen-induced arthritis mouse model in DBA/1 mice. The therapeutic effect of the nanogel in suppression of the onset of arthritis in each paw of mice was as effective as dexamethasone, a commercial anti-rheumatoid arthritis drug. Therefore, our findings may suggest a potential biomedical application for clinical translation.

**4:00 PM BM09.13.08**
**Self-Assembled Nanocomplex of Prodrug-Mediated Polymer Architecture for Stimuli-Responsive Intracellular Gene Silencing with Chemotherapy** Sungjin Jung, Jinhwan Kim, Swapan Pramanick, Hyeongmok Park, Hyori Lee, Junseok Lee and Won Jong Kim; Pohang University of Science and Technology, Pohang, Korea (the Republic of).

Nanostructured materials have been attracted much attention as effective delivery carrier for cancer treatment because nano-sized materials exhibit tumor site-specific accumulation by inherent leaky vascular structure in cancerous region, known as enhanced permeability and retention (EPR) effect. Conventional chemotherapy using single anti-cancer drug has been impeded by inherent nature of cancer including fast mutagenesis and drug resistance, thus nanostructured carrier for combinatorial gene and chemotherapy has attracted a huge attention, which leads cancer cells to be vulnerable against chemotherapeutics by altering the intrinsic drug-resistance pathway of cancer in genetic level. However, the loading process of multiple cargos into nanostructured carrier is not orthogonal, which affects not only the structure of carrier but also the loaded amount of each cargo molecule. Therefore, development of a nanostructured carrier which facilitate orthogonal loading of the cargo molecules has been highly demanded. Herein, we report an ingeniously designed Pt(IV)-mediated polymeric architecture (Pt-PA) for combinatorial gene and chemotherapy to address the issue. The Pt(IV) prodrug, which has two reaction site, enabled the crosslinking of low-molecular-weight (MW) polyethyleneimine (PEI) to form high-MW PEI. Accordingly, the Pt-PA exhibited successful self-assembly into nano-sized complex with therapeutic gene (i.e. siRNA) without any influence on the loading of Pt(IV), because Pt(IV) has been already incorporated in a polymer architecture by chemical conjugation. The self-assembled complex could be dissociated specifically under redox environment due to an inherent characteristic of the Pt(IV) crosslinker. Therefore, simultaneous release of both active Pt(II) drug and gene was monitored at intracellular reducing environment, resulting in enhanced gene silencing effect and anticancer effect. In animal study, an improved therapeutic effect of the nano-sized complex was observed, which can be explained by tumor targeting via EPR effect of nano-sized complex as well as enhanced intracellular release of drug and siRNA at reducing environment. Taken together, overall results from in vitro and in vivo studies strongly manifest the therapeutic potential of our nanostructured Pt(IV)-mediated polymer architecture.

**4:15 PM BM09.13.09**
**Facile Formulation of poly(phenylboronate) Nanoconstruct by Simple Mixing with Diol-Containing Hydrophobic Chemotherapeutics and Its Biomedical Application** Junseok Lee, Jinhwan Kim, Yeong Mi Lee and Won Jong Kim; POSTECH, Pohang, Korea (the Republic of).

To date, self-assembled nanostructures have drawn enormous attention for biomedical application. Since nano-scaled particulates are known to be accumulated into the tumors easily via an enhanced permeation and retention (EPR) effect, such nanostructures have been exploited as delivery system for therapeutic small molecules. However, convoluted synthetic process of conventional nanostructures has impeded to achieve feasible and reproducible clinical applications. Herein we report a facile formulation of self-assembled nanostructure for systemic delivery of diol-containing hydrophobic chemotherapeutics, andrographolide (AND) and doxorubicin (DOX). In these studies, formation of a stable nanoconstruct enabled to enhance the water solubility of AND or efficiency of DOX. Phenylboronic acid (PBA) was grafted on the hydrophilic polymer to form poly(phenylboronate) (pPBA) and nanoconstruct was easily formulated by simple mixing with drug through the formation of phenylboronic ester with 1,3-diol of drugs. The release profile of drug was pH-responsive owing to the intrinsic property of phenylboronic ester. Moreover, tumor targeting ability of nanoconstruct was demonstrated in vitro and in vivo driven by an inherent property of residual PBA. Finally, antitumor effect of nanoconstruct was highly effective in vivo even in comparison with free drug. Taken together, our judiciously designed pPBA/drug nanoconstruct suggests a new paradigm of self-assembled nanostructure with variant potential in biomedical application.