NATURE-INSPIRED CHEMICAL ENGINEERING, A TRANSFORMATIVE METHODOLOGY FOR INNOVATION

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Key Words: Nature inspired chemical engineering, process intensification, sustainability, scalable manufacturing, efficiency, resilience

Some of our greatest challenges involve clean energy, water, the environment, dwindling resources, sustainable manufacturing, and healthy ageing. To approach them, chemical engineers are well equipped with the basic tools: balances, systems modeling, thermodynamics, kinetics and transport phenomena. Nevertheless, how these tools are employed in process and product design requires rethinking. Tackling Grand Challenges requires step-changes through transformative approaches and lateral thinking across disciplines, beyond incremental variations on traditional designs.

Nature is filled with well-integrated, “intensified” systems, optimized over the eons, to satisfy stringent constraints for survival by scalable processes with emergent properties. We propose to take nature as a source of inspiration, leveraging fundamental mechanisms underpinning desirable properties (like scalability, resilience or efficiency) and applying these to engineering designs, with suitable adaptations to satisfy the different contexts of technology and nature. We call this approach *Nature-Inspired Solutions for Engineering* (NISE), and its application to chemical engineering problems *Nature-Inspired Chemical Engineering* (NICE) [1].
The need to think about the context of technological applications, and the consistent use of fundamental scientific insights rather than superficial similarities, sets nature-inspired engineering apart from biomimetics or biomimicry. Examples from architecture and structural engineering will be given to illustrate this difference [2]. This lecture will introduce NICE as a systematic methodology [1] that is thematically structured around ubiquitous, fundamental mechanisms in nature, in particular: (T1) hierarchical transport networks, (T2) force balancing, (T3) dynamic self-organization, and (T4) control mechanisms in ecosystems, biological networks and modularity.

Thus, NICE looks at nature with the eyes of an engineer, employing scientific tools to derive nature-inspired concepts that are, subsequently, systematically used in the nature-inspired design of solutions to real problems, aided by mathematical and computational modeling and experimentation. In our examples, we will see how we learn from trees, lungs, kidneys, and dunes to intensify chemical and energy processes, and how we discover materials for biomedicine and the built environment, using the NICE methodology [1-6].

The NICE approach is powerful, because it allows us to merge creativity with rational design. Being thematic and systematic, once validated for one problem, NICE can be employed to solve various similar problems in other fields, e.g., from fluidized beds to fuel cells, and from catalysts to dental materials. Ultimately, the NICE methodology is a practical pathway for innovation and design.

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FROM PLANT TO PRODUCT – BASIC PRINCIPLES, APPLICATIONS AND FUTURE PROSPECTS

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Keywords: Plants, functional morphology, biomechanics, Cactaceae, Lotus-Effect, Martyniaceae

Plants have served as indispensable resource all through the history of mankind. Food, fibres, building materials, fuel or secondary metabolites for medical treatments are only a few examples for the importance of plants in everyday life. In recent decades, plants have gained increasing interest as models for improved components or materials in engineering, if not as key to completely novel solutions for certain problems. One of the most prominent examples deals with plant surfaces, the properties of which, especially regarding attachment of insects, wetting with water, or the application of chemicals have been a research topic for almost one hundred years. However, the publication about the connection between wetting properties and the removal of contaminating particles in 1997 [1], that became popular under name “Lotus-Effect”, initiated a new interest in functional surfaces resulting in a boost of investigations dealing with self-cleaning properties and related phenomena [2]. Despite the vast amount of research, the number of commercially successful applications is still limited. Here, a short overview is given about the basis for water-repellency in plants and animals, examples for the successful transfer from a biological into a technical system and finally results will be presented of recent research activities.
The second part deals with the particular role of cell walls and their contribution to mechanical stability and function of the whole plant body or individual organs. Examples will be given from Cactaceae [3] and Martyniaceae [4]. In columnar Cactaceae the sophisticated arrangement of fibres not only results in a very thin walled tubular wood tissue but more specifically in a highly resilient connection between stem and branch that finally served as inspiration for newly designed light weight carbon and glass fibre reinforced components. In Martyniaceae, the fruits develop into a highly specialised capsule adapted to the dispersal by large animals. Fruit development, especially the formation of sclerenchymatous tissue combined with the unusual arrangement of fibres and its implication for the mechanical properties will be discussed in the light of demands for future bioinspired materials.

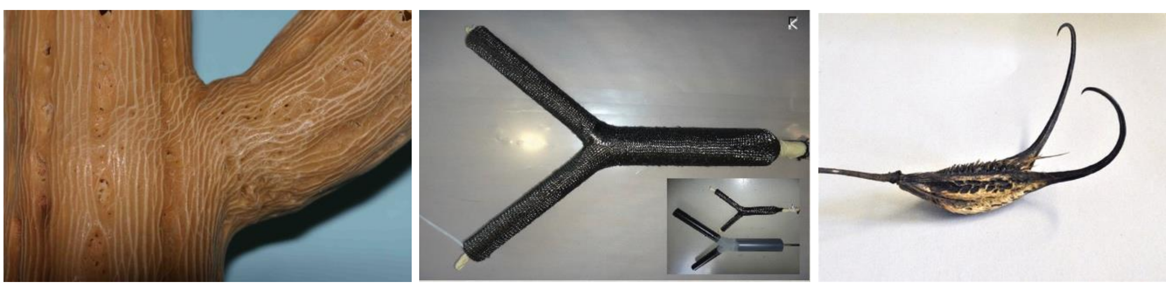

Fig. 1: the stem branch junction of columnar Cactaceae (left) served as model for a novel carbon fibre reinforced component in light weight construction (center). The fruits of *Proboscidea* (right) consist of sclerenchymatous fibres only, but exhibit superior mechanical properties und different load conditions.

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NATURE INSPIRED ARCHITECTURE: INTEGRATIVE COMPUTATIONAL DESIGN AND FABRICATION FOR FILAMENTOUS STRUCTURES

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Key Words: Nature inspired architecture, biomimetic structures, computational design and construction

Inspiration found in nature, together with advances in computational design and robotic fabrication, challenge existing approaches in building technology in a surprising manner, or even point out completely different possibilities. Biology offers an almost inexhaustible reservoir of principles of form, structure and process that can be transferred to architecture. At the same time, computation profoundly transforms the building industry. Our presentation will introduce ways of tapping the full potential of digital technologies in architecture and construction through inspiration by nature, in order to go beyond the mere digitalization of established planning procedures and the automation of existing building processes towards truly integrative computational design and construction. Along the example of large-scale, load-bearing, fiber-composite structures, we will show how a biomimetic approach enables creating architecture that is both highly effective and efficient, as well as explorative and expressive.

Diversity constitutes a key feature of living nature. Highly differentiated, finely tuned and infinitely varied systems are unfolding from evolutionary development. Given this vast range of natural variation, it may come as a surprise that almost all load-bearing biological structures are fibrous composites. They are all made-up of filamentous elements embedded in a matrix material. While these two elements remain distinct in the composite material, their combination yields properties and performances superior to each of the two constituting parts. In this way, natural composites fundamentally work in a similar manner as man-made, technological composites, such as glass or carbon fibre-reinforced plastics. This correspondence in basic composition and characteristics renders fibrous composites as prime candidates for biomimetic design research that investigates how the principles of fibrous organisation in biology can be transferred to composite systems in architecture.

We will present interdisciplinary research of the Institute for Computational Design and Construction at the University of Stuttgart that seeks to bridge between the technical dimension of fibrous systems in architecture and the rich repertoire of fibrous morphology in nature. Based on advanced design computation, simulation and robotic fabrication these explorations open-up a new approach to fibre-reinforced composite structures. This will be introduced along the example for several full-scale demonstrator buildings, which are made entirely from load-bearing fibre composite components. They are each produced from glass and carbon fibres through novel, robotic additive fabrication processes, which allow for the specific adaptation of form and fibre layout for each individual building element depending on its structural and architectural requirements.

Figure 1 – Robotic filament winding of large-scale building elements

Figure 2 – Full-scale research demonstrator: Elytra Filament Pavilion, V&A London

THE BIOLOGICAL OXIDATION INSPIRED BIOMEDICAL HYDROGELS

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Key Words: Biological oxidation, Hydrogel, Enzyme, Polymerization, Biocatalysis

Due to its 3D crosslinked networks and adjustable physicochemical properties, hydrogels have been widely applied in tissue engineering, drug-delivery system, pollution regulation, polymer electrolyte, agricultural drought-resistance, cosmetic and food area. However, the harsh prepared conditions and high chemical residues of traditional hydrogel both seriously limited their bio-related applications. We introduced the recent advances on tandem enzyme complex for the radical polymerization and further 3D bio-printing of hydrogel.[1,2] We also demonstrated that substrate channel in hydrogel networks can benefit the superactivity of the laden cascade enzymes, which can realize the industrial application of biological oxidation. Finally, we fabricated an enzyme-laden nanogel to mimic neutrophils for antimuor via cascade enzymatic elevation of ROS. This novel biochemical approach is highly useful for cancer therapy. [3,4,5]

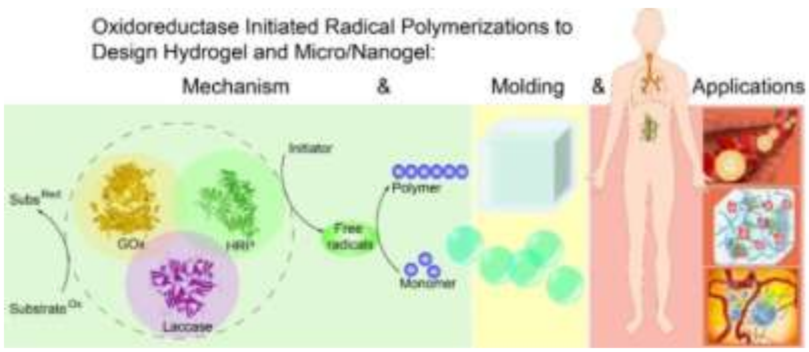

Figure 2 –Enzymes triggered preparation and application of hydrogel

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THERMAL INSULATION DESIGN BIOINSPIRED BY MICROSTRUCTURE STUDY OF PINGUIN FEATHER AND POLAR BEAR HAIR

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Key Words: thermal insulation, fibers; keratin, feather; hair; porosity

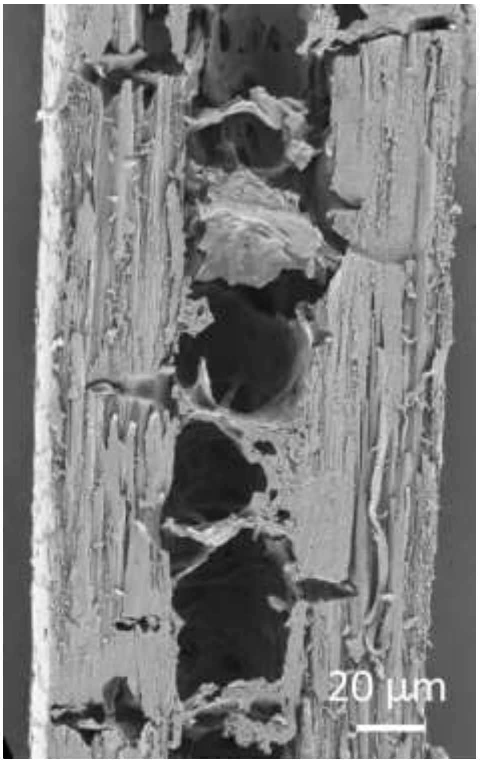

Figure 3. SEM micrograph of the longitudinal cut through the polar bear hair exposing the internal structure with hollow channels through the cortex.

In nature, thermal insulation structures, such as penguin feather and polar bear hair, are well developed; enabling the animals' survival in frigid waters. The detailed microscopy investigations conducted in this study, allowed us to perform microstructural analysis of these thermally insulating materials, including statistical measurements of keratin fiber and pore dimensions directly from high resolution Scanning Electron Microscope (SEM) images. We revealed many similarities in both materials: penguin feather and polar bear hair, and showed the importance of their hierarchically-organized porous structure. The porosity is present in the main shafts and also on the external surfaces. The hierarchical porosity observed in both materials at different structural levels that are often interconnected. The cortex is based on aligned bundles of keratin fibers, with the average diameter 0.3-0.6 µm and fibers run parallel to each other along the length of the shaft, see Figure 1. The keratin fibers have a similar diameter in the range of 0.14-0.18 µm, even though polar bear hair is composed of coiled-coil alpha-keratin and penguin feather of sheets of beta-keratin. Our findings from a unique comparison between two keratin-based materials, penguin feather and polar bear hair, shed new light on how their microstructure is optimized to form highly insulating materials [1]. High-resolution SEM allows us to observe their 3D structure, including statistical measurements of keratin fiber and pore diameters, in greater detail. These optimized thermal-insulator systems indicate the road maps for future development, and new approaches in the design of material properties.

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NATURE-INSPIRED. MULTI-FUNCTIONAL SURFACE COATINGS FOR SPACE APPLICATIONS, FABRICATED BY ADDITIVE MANUFACTURING

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Key Words: Multi-functional surface coating, humidity absorption, capillary action, additive manufacturing, space application

Conditions in space are extreme. Nevertheless, the goal for the indoor environment on the International Space Station (ISS) remains the same as on Earth: to provide comfort and a healthy quality of life. The environmental control and life-support system (ECLSS) is, among others, responsible for the absorption of humidity from cabin air, which is treated, stored, and re-used. However, efficiency could be improved, as only 70-93% of water is recyclable, and costly resupply from Earth is needed. Additionally, astronauts on the ISS experience 0.5 Sv of ionizing radiation in one year, consisting of galactic cosmic rays (GCR) and solar particle events (SPE). Beyond Earth's magnetic field this can increase immensely, due to potential solar flares, leading to the biggest risk to astronauts' health, including experience of radiation syndrome and cancer, but, furthermore, threatens future bio-regenerative ECLSS. Furthermore, with humidity of more than 60%, organisms such as bacteria and fungi start to disperse and proliferate. The weakened immune system of astronauts, limited treatment, no immediate return to Earth, and increasing resistance of bacteria, reinforces the control of microbial contamination. Currently, neither of the above is feasible for future missions to Moon, Mars, and beyond and, therefore, finding new approaches for regenerative life support through passive systems is crucial.

Here, we present the design of a nature-inspired, multi-functional surface coating that takes advantage of the humidity produced by astronauts' indoors activities. This surface consists of hydrophobic microstructures that are able to transport humidity passively, via capillary action, through structures containing microchannels. They are inspired by cicada wings, human and moth eyes (*Figure 1a*), abstracted into pillar shaped and inverted cone and cone shaped structures, respectively (*Figure 1b*), and designed into multi-functional vase-shaped microstructures (*Figure 1c*). The artificial surface structures are fabricated by additive manufacturing (*Figure 1d*).

It can be estimated that the microstructures' increase in performance under microgravity conditions as capillary-dominated systems are supported 1000 times more in space, due to the lack of gravitational forces. The structures further could repel bacteria and support radiation shielding as the hydrogen contained in water stops protons in SPE, fragments heavy ions in GCR, and slows down neutrons formed as secondaries. Advantages of this multi-functional surface coating include a better understanding of life comfort and health for astronauts regarding room quality, bacteria, and ionizing radiation, as well as an improved understanding of passive water systems, and, therefore, the reduction of energy consumption, and a better understanding of controlled humidity absorption for applications in space and on Earth.

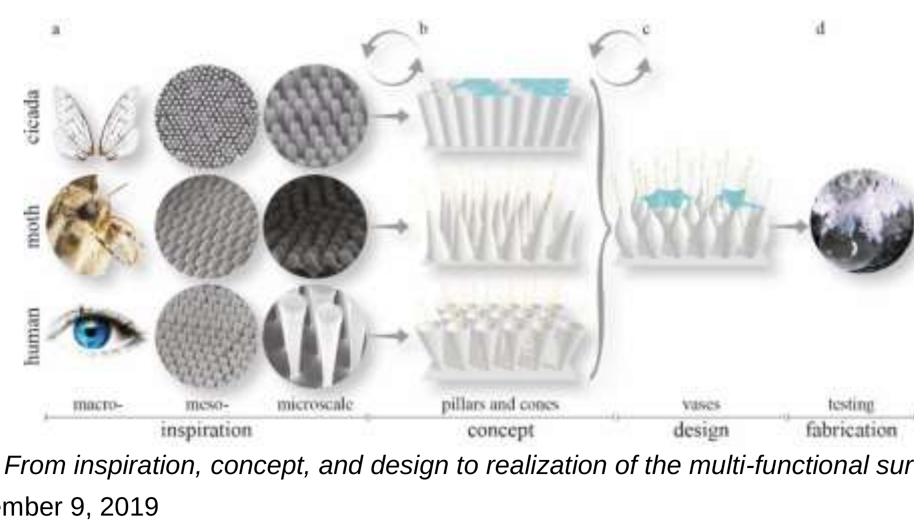

Figure 4 – From inspiration, concept, and design to realization of the multi-functional surface coatings.

BULK SUPERCRYSTALLINE CERAMIC-ORGANIC NANOCOMPOSITES: NEW PROCESSING ROUTINES AND INSIGHTS ON THE MECHANICAL BEHAVIOR

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Key Words: Supercrystal, Nanocomposite, Ceramic, Hierarchical Material, Mechanical Behavior.

In the strive to produce nature-inspired hierarchical materials with an enhanced combination of mechanical properties, supercrystalline ceramic-organic nanocomposites have been produced in bulk form and characterized from a variety of perspectives. Through an interdisciplinary collaboration at the crossroad between materials science, chemistry and mechanical engineering, a bottom-up approach has been designed. It consists of a sequence of self-assembly, pressing and heat treatment, and it leads to macroscopic poly-supercrystalline materials with exceptional mechanical properties and behavior. The crosslinking of the organic phase induced by the heat treatment does not only increase the materials' stiffness, hardness and strength (elastic modulus up to 70 GPa, hardness up to 5 GPa and bending strength up to 630 MPa), but alters also their constitutive response. Fracture toughness values higher than theoretical predictions have emerged (~ 1 MPa·$m^{1/2}$), implying the presence of extrinsic toughening mechanisms, such as the crack-path deviation observed at indents' corners. Ex-situ nanoindentation and in-situ SAXS/microcompression studies also suggest the possibility for supercrystalline materials to accommodate compressibility and plastic-like deformation. Defects analogous to the ones typically observed in crystalline lattices, such as stacking faults, dislocations and slip bands, are detected at the superlattice scale (even if one order of magnitude larger than the atomic one, and with interactions among the nano-building blocks controlled by the organic phase). Correlations between defects, processing and mechanical properties have been drawn by adapting the classic theories of mechanical behavior of materials. These same materials are additionally being used as bricks for the development of novel hierarchical composites, via additive manufacturing or fluidized bed techniques.

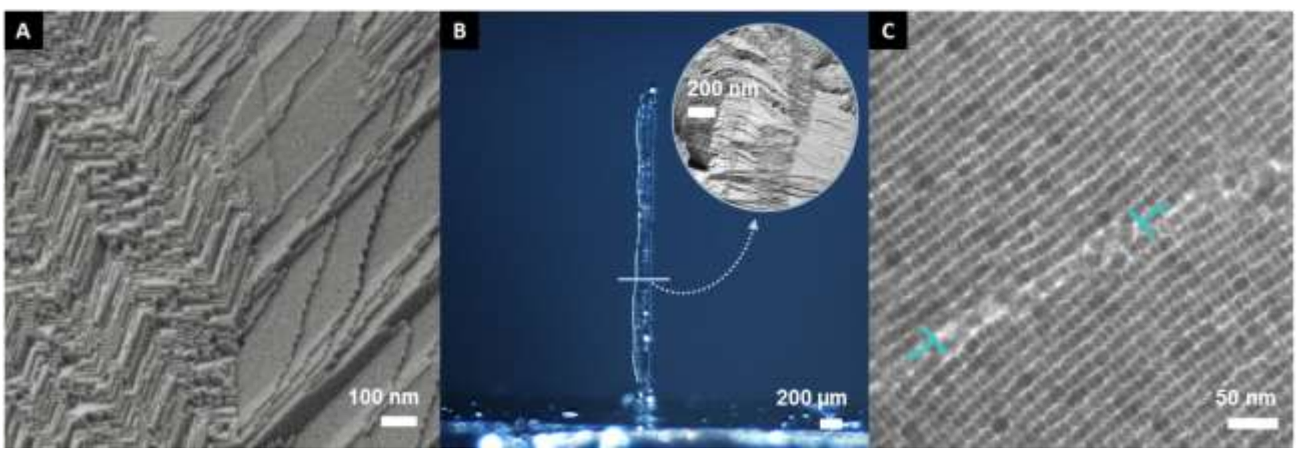

Figure 1 – (A) Structure of poly-supercrystalline nanocomposite; (B) 3D-printed supercrystalline pillar and its nanostructure; (C) edge dislocations inside bulk supercrystal.

BIOINSPIRED MECHANICALLY DURABLE SUPERLIQUIPHILIC/PHOBIC SURFACES

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Living nature, through some 3 billion years of evolution, has developed materials, objects, and processes that function from the nanoscale to the macroscale. The understanding of the functions provided by species and processes found in living nature can guide us to design and produce bioinspired surfaces for various applications[1,2]. There are a large number of flora and fauna with properties of commercial interest. Nature provides many examples of surfaces that repel (hydrophobic) or attract (hydrophilic) water. The most famous is the lotus leaf. Its surface contains a hierarchical structure that, combined with specific surface chemistry, results in a water repellant surface that is self-cleaning, as water droplets collect contaminants as they roll off. Some plant leaves, such as fagus leaves, are hydrophilic, allowing water to rapidly spread into a thin layer, increasing evaporation, leading to a dry and self-cleaning surface. By taking inspiration from nature, it is possible to create hierarchically –structured surfaces with re-entrant geometry and surface chemistry that provide multifunctional properties including superliquiphilicity/phobicity, self-cleaning/low biofouling, and/or low drag.

A facile, substrate-independent, multilayered nanoparticle/binder composite coating technique has been developed to produce various combinations of water and oil repellency and affinity with self-cleaning properties[3]. These coatings having a so-called re-entrant geometry can also repel surfactant-containing liquids. Some of the nanostructured surfaces have been found to be anti-bacterial[4]. These coatings provide the basis to fabricate surfaces for a range of applications including self-cleaning, anti-fouling, anti-smudge, anti-fogging, anti-icing, low drag, water purification, and oil–water separation[1,5,6]. The coatings have been found to be mechanically durable and some, optically transparent.

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UNEXPECTED STABILITY OF AQUEOUS DISPERSIONS OF RASPBERRY-LIKE COLLOIDS

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Key Words: colloids, colloidal stability, raspberry-like particles, self-assembly.

Colloids are microscopically small substances that spread out uniformly through another material and don't settle to the bottom. When the material is a fluid, the result is a colloidal solution, dispersion or suspension. Natural and artificial colloidal solutions are common in everyday life and include fog, hair sprays, paints, milk, hand lotion and jellies. These solutions are particularly important in the medical field, where they are often used in intravenous solutions to regulate blood conditions and other functions. However, the applicability of colloidal solutions is limited by their stability under certain conditions.

Inspired by the morphology of virus and their high stability in blood conditions, we designed a type of unique colloids, raspberry-like colloids, that remain stable in a variety of conditions (Figure 1).[1] The colloids are synthesized in a single step, making the process more efficient and sustainable than traditional multi-step methods. The procedure involves injecting acrylate monomers, styrene and the cross-linker divinylbenzene into a water-ethanol solution and inducing simultaneous dispersion and emulsion polymerisation of the ingredients. The resulting particles fuse to the final shape of the raspberry-like colloids in the presence of the cross-linker. These raspberry-like colloids show unexpected stability against aggregation over large variations of added salt concentrations without the addition of any stabilisers. Derjaguin–Landau–Verwey–Overbeek (DLVO) calculations are performed to illustrate the relationship between the unusual colloidal stability and particle morphology. Furthermore, the raspberry's stability is applied to prepare superspheres and thin films in which the raspberry-like colloids self-assemble into hexagonally close-packed crystals with exquisite reproducibility. Our raspberry colloids thus offer a broader perspective on the role of particle morphology in colloidal stability and could be readily exploited in applications such as photonic ink, drilling muds, sustainable paints, food additives and drug delivery that demands high colloidal stability under salted conditions.

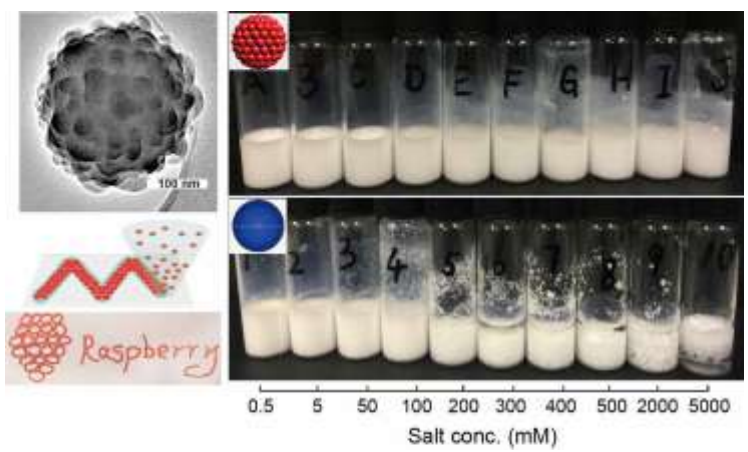

Figure 5 – TEM image of the raspberry-like colloids (top left); Colloidal stability of raspberry-like colloids (top right) and smooth colloids (bottom right) in salted water; Self-assembly of raspberry-like colloids into photonic materials (bottom left).

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STRUCTURE-PROPERTY RELATIONS OF HIGHLY ORDERED BIO-NANOCOMPOSITES

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Key Words: bio-nanocomposite, nacre-mimetic, montmorillonite, gelation.

Bio-nanocomposites with superior mechanical, transport and flame-retardant properties can be produced from the combination of biopolymers and silicate nanoclay platelets, such as montmorillonite (MMT) [1,2,4]. The highly ordered nanostructure observed in such systems is often compared to natural ones, such as in the brick-and-mortar arrangement of aragonite plates in nacreous materials [3]. Previous work on nacre-mimetic alginate/MMT nanocomposites has shown good compatibility between the biopolymer and inorganic filler and a dependence on MMT concentration to the level of alignment [4]. In this study, we investigate the effect of gelation on the orientation of nanoparticles and its impact on clay stacking and effective aspect ratio. Thermo-reversible gelling biopolymers, i.e. gelatin and carrageenan, were used as matrices to induce early gelation; and compared to sodium alginate (late gelling reaction). Self-supporting bio-nanocomposite films based on gelatin or carrageenan, with a wide range of Na-montmorillonite concentration – up to 80 wt.% MMT – were successfully prepared by solvent casting. The obtained films display a highly aligned nacre-like structure (Fig. 1). To investigate the effect of MMT ordering on the mechanical properties, we have analyzed the obtained films with dynamic mechanical thermal analysis. The bio-nanocomposite films display exceptional mechanical properties, with storage modulus as high as 33 GPa (carrageenan/MMT); and high reinforcement depending on MMT concentration (Fig. 2). At remarkably high inorganic fraction, 80 wt.% MMT, early gelling biopolymers showed a continued increase in material reinforcement, whereas late gelation shows a slight decrease. This suggests that early gelling might reduce restacking of MMT platelets, thus, improving the effective aspect ratio of the filler. The highly ordered structure observed in the gelatin 80 wt.% MMT composite was also reflected in its high heat distortion temperature, implying lower oxygen diffusivity. To better understand the influence of gelation and MMT addition on the mechanical properties, we further applied a conventional composite theory (Halpin-Tsai model), which considers the individual contributions of filler, such as the level of alignment, aspect ratio, volume fraction, and the modulus of the MMT platelets.

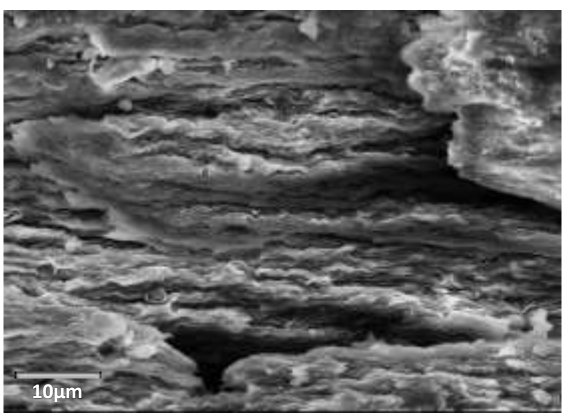

Figure 1 – ESEM micrograph of gelatin 80 wt.% MMT bio-nanocomposite cross-section.

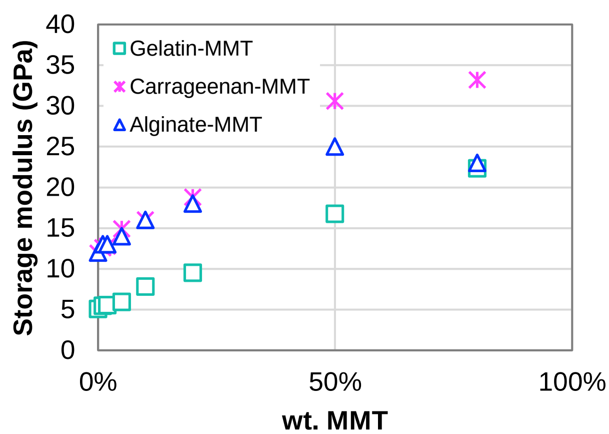

Figure 2 – Storage modulus of bio-nanocomposites with highly aligned MMT platelets in different matrices (gelatin, carrageenan, alginate).

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NATURE INSPIRED SOLUTIONS SPECIAL INTEREST GROUP – A UK WIDE NETWORK

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This is not an academic paper. Marc-Olivier Koppens, UCL suggested that I hand in a talk outline.

Key Words: Nature inspired solutions, UK network, acceleration of growth, help solve industry problems

Innovate UK
Knowledge Transfer Network

This talk wants to give an overview of the newly founded nature inspired solutions special interest group (NIS SIG) which is a UK network of Nature inspired engineering solution providers and industry problem holders that can benefit from Nature Inspired solutions.

What is the NIS SIG aiming to do?
Like all SIGs run by KTN, the aim is to convene people who wouldn't normally meet; to learn, connect and explore opportunities. The SIG will initially focus on the application of NIS across transport, infrastructure and energy. Over the next two years, we will build a community (online and offline), organise networking events, showcases and raise awareness by sharing best practice and success stories. A landscape map and a commercial opportunity report will be created to help accelerate growth and market uptake in the relevant sectors.

Joining the NIS SIG provides an opportunity to:

- Discover how nature inspired engineering can help you solve some of your biggest challenges.
- Seek support from the NIS community if you are a 'challenge holder'.
- Showcase your research and demonstrate your nature inspired engineering solutions.
- Broaden your network and make meaningful connections leading to collaboration opportunities.

The talk wants to give an overview of the activities in Nature Inspired Engineering in the UK, inform about the NIS SIG activities and find out where there are synergies with other countries and regions.

Here is an example of an event that we ran on 25th April to showcase nature inspired solutions.
https://ktn-uk.co.uk/news/can-bees-dragonflies-and-locusts-help-solve-connected-and-autonomous-vehicle-problems

Join our LinkedIn Group: Nature Inspired Solutions at KTN- https://www.linkedin.com/groups/13701855/
The talk would be best places in an overview section where various topics are discussed. As it ties in Energy, Infrastructure and Transport, the three conference streams would be best, if this does not exist:
•*Built Environment: Construction, Architecture & Urban Design*
•*Energy & Environmental Technology*
•*Robotics and Other Applications*

I am happy to discuss the angle and topic of the talk, just get in touch via email: monika.dunkel@ktn-uk.org

I would also be interested to chair a session if needed, as I have a generalistic overview of various of the mentioned conference themes, best in one of the three areas mentioned above.

IS DIRECT AIR CAPTURE NATURE-INSPIRED?

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Key Words: Direct Air Capture, Moisture Swing, Artificial Trees, Active Membrane, Energy Transition

The very concept of carbon dioxide removal from the atmosphere is nature-inspired. Plants take CO_2 from the atmosphere and convert it to reduced carbon. Combining direct air capture with renewable energy to produce synthetic fuels mimics photosynthesis. However, the scale of agriculture, silviculture or aquaculture that could balance the anthropogenic carbon budget dwarfs current world agriculture. This points to the need for process intensification and non-biological, technical approaches to remove excess carbon from the environment.

Closing the anthropogenic carbon cycle without direct air capture is difficult. While air capture could be nature-inspired, it would have to outperform natural processes. The IPCC hints at the difficulty of this challenge. The Fifth Assessment Report and the Special Report on Global Warming of 1.5°C both emphasize the need for negative emissions, but only discuss bioenergy with carbon capture and storage (BECCS). They do not offer a transition from natural processes to advanced, nature-inspired technologies. Early implementations of direct air capture show little inspiration from nature. Fans, blowers and thermal swings mimic flue gas scrubbing rather than natural processes. However, a new generation of designs takes its cues from natural systems. Passive systems that avoid blowers and let wind flow over surfaces face mechanical problems akin to those that nature solved in the design of a tree. Not only is it necessary to make good contact between gas-solid exchange surfaces, but contactors must also operate over a wide range of natural wind speeds. Low wind speeds limit air exchange; high speeds stress structural supports. Passive collection of CO_2 from air also sidesteps Sherwood's Rule, which would have the cost of direct air capture equal the cost flue gas capture multiplied by the ratio of CO_2 concentrations. Sherwood's Rule, if it were to apply, would render direct air capture hopelessly expensive.

Passive systems will likely scale up in numbers rather than size, raising challenging issues of how to control and integrate the output of thousands if not millions of subsystems without armies of operators. This calls for process intensification, automation and feedback controls well beyond those in conventional process engineering. It will require inspiration from the exquisite feedback and control strategies exhibited in natural systems.

With regard to chemical capture mechanism, nature-inspired technologies offer additional opportunities from the study of interactions of water and CO_2. A particularly interesting class of sorbents use the presence or absence of water to modulate the affinity of the sorbent to CO_2. These moisture swing sorbents control the availability of hydroxide ions for CO_2 sorption by controlling the behavior of water in small hydrophobic pores inside the structure of a polymer sorbent. A case can be made that carbonic anhydrase performs a similar task and that one therefore can learn from biological analogs. More generally, these moisture swing sorbents shed light on complex properties of water which equally govern biological systems.

Recent developments, moving well beyond conventional sorbent technology, aim for actively pumping membranes made from moisture swing sorbents. These membranes take advantage of moisture differentials across a membrane and the resulting chemical potential to pump CO_2 into the interior of a hollow fiber. The exergy of evapotranspiration moves the fluid and pushes the CO_2 against a chemical potential into the fiber. The design has a remarkable similarity to the vascular systems of a tree. Leaves, via evapotranspiration, pull up a carbonate brine, load it with CO_2 and return it to the root of the tree, where the captured CO_2 is removed.

Direct air capture can help close the world's carbon budget. By sequestering the captured CO_2, it can reduce the CO_2 concentration in the atmosphere. It also can provide a chemical feedstock to produce fuels from renewable energy. These fuels create the storage capacity necessary for the deep penetration of intermittent renewable energy into the world's energy infrastructure. The introduction of synthetic liquid fuels enables a gradual evolutionary approach to the global energy transition. Long after fossil fuels will be phased out, the carbon cycle has been closed and the climate is stabilized, synthetic methane, gasoline, diesel and jet-fuel can support the existing infrastructure. These fuels will then be gradually replaced with energy carriers that owe nothing to petroleum. Evolutionary principles tested in nature suggest that such gradual transformations offer more stability than a radical and sudden overhaul of the entire energy infrastructure.

NATURE-INSPIRED FLOW-FIELDS AND WATER MANAGEMENT FOR PEM FUEL CELLS

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Key Words: Lung-inspired flow-field, PEM fuel cell, Water management, Gas distribution

Flow-field design is crucial to polymer electrolyte membrane fuel cell (PEMFC) performance, since non-uniform transport of species to and from the membrane electrode assembly (MEA) results in significant power losses. The long channels of conventional serpentine flow-fields cause large pressure drops between inlets and outlets, thus large parasitic energy losses and low fuel cell performance.

Here, a lung-inspired approach is used to design flow-fields guided by the structure of a lung. The fractal geometry of the human lung has been shown to ensure uniform distribution of air from a single outlet (trachea) to multiple outlets (alveoli). Furthermore, the human lung transitions between two flow regimes: 14-16 upper generations of branches dominated by convection, and 7-9 lower generations of space-filling acini dominated by diffusion. The upper generations of branches are designed to slow down the gas flow to a rate compatible with the rate in the diffusional regime (Pé ~ 1), resulting in uniform distribution of entropy production in both regimes.

By employing a three-dimensional (3D) fractal structure as flow-field inlet channel, we aim to yield similar benefits from replicating these characteristics of the human lung. The fractal pattern consists of repeating “H” shapes where daughter “H’s” are located at the four tips of the parent “H”. The fractal geometry obeys Murray’s law, much like the human lung, hereby leading to minimal mechanical energy losses. Furthermore, the three-dimensional branching structure provide uniform local conditions on the surface of the catalyst layer as only the outlets of the fractal inlet channel are exposed to the MEA.

Numerical simulations were conducted to determine the number of generations required to achieve uniform reactant distribution and minimal entropy production. The results reveal that the ideal number of generations for minimum entropy production lies between N = 5 and 7. Guided by the simulation results, three flow-fields with N = 3, 4 and 5 (10 cm^2 surface area) were 3D printed *via* direct metal laser sintering (DMLS), and experimentally validated against conventional serpentine flow-fields. The fractal flow-fields with N = 4 and 5 generations showed ~20% and ~30% increase in performance and maximum power density over serpentine flow-fields above 0.8 A cm^{-2} at 50% RH. At fully humidified conditions, though, the performance of fractal N = 5 flow-field significantly deteriorates due to flooding issues.

Another defining characteristic of the fractal approach is scalability, which is an important feature in nature. Fractal flow-fields can bridge multiple length scales by adding further generations, while preserving the building units and microscopic function of the system. Larger, 3D printed fractal flow-fields (25 cm^2 surface area) with N = 4 are compared to conventional serpentine flow-field based PEMFCs. Performance results show that fractal and serpentine flow-field based PEMFCs have similar polarization curves, which is attributed to the significantly higher pressure drop (~ 25 kPa) of large serpentine flow-fields compared to fractal flow-fields. However, such excessive pressure drop renders the use of a large scale serpentine flow-field prohibitive, thus favouring the fractal flow-field.

A major shortcoming of using fractal flow-field is, though, susceptibility to flooding in the gas channels due to slow gas velocity. This problem has led to the development of a nature-inspired water management mechanism that draws inspiration from the ability of the Thorny Devil (Australian lizard) to passively transport liquid water across its skin using capillary pressure. We have recently integrated this strategy with the fractal N = 4 flow-fields and verified the viability of the strategy using neutron imaging at Helmholtz-Zentrum Berlin (HZB). Implementation of this water management strategy is expected to circumvent remaining problems of high-generation fractal flow-fields.

ELECTROCHEMICAL MATERIALS DISCOVERY AND INTELLIGENCE

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Key Words: Materials Discovery, Artificial Intelligence, CO2 Conversion, Electrocatalysis, Machine Learning

Design and implementation of efficient and cost-effective electrochemical devices is a complex challenge. It hinges on big-data driven knowledge at the frontiers of multi-disciplinary efforts in materials discovery and design. These massive data–driven processes, however, require intensive cognitive, yet expensive systems, including human, to determine the best design decisions. A novel approach towards Artificial Intelligence (AI) and Machine Learning (ML) algorithms can overcome the complexity of selecting advanced new materials with the predictable and desired properties. Focusing on advanced electrocatalysts for CO2 conversion as a use case, we demonstrate an AI-driven “Virtual Materials Intelligence” platform (beta) for materials data management and intelligent design equipped with an advanced user interface and predictive capabilities in view of materials properties and function. The platform combines information originating from large data sets of different origins. The data storage, data analysis, and advanced analysis algorithms enable efficient and secure data flow between several different simulation and characterization activities. The cloud-based platform ultimately aims to manage all available materials databases and relevant modeling, simulation, performance, cost, and characterization data and how they can be communicated to materials fabrication and design teams.

NONEQUILIBRIUM THERMODYNAMICS AND CONSTRUCTAL LAW
GUIDELINES FOR NATURE INSPIRED CHEMICAL ENGINEERING PROCESSES

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Key Words: chemical processes, nonequilibrium thermodynamics, constructal law, thermodynamic efficiency.

The chemical engineering specialty deals with the processing of matter and energy, with a special emphasis on designing and operating technological apparatus for the large-scale production of chemicals and the manufacture of products with desired properties through chemical processes. Matter and energy processing can be extended to information, especially at the chemical plant scale, covering areas similar to what Nature processes.

Within the sustainable growth challenges now everywhere, Nature is a realistic model of structures and processes, whose performance, efficiency and resilience can be envied by human-made activities.
However, nature-inspiration is far from being the norm in chemical engineering. Indeed, chemical engineering textbooks and handbooks show that chemical engineering processes are designed and operated on the basis of phase equilibrium hypotheses in reaction and separation engineering, that transport phenomena are usually described with linear phenomenological law and that process regulation is also mostly done with linear control theory. Most of these concepts are decades old.

Nature inspiration could help improve performance, efficiency and resilience of chemical engineering processes. To achieve this goal, the challenges have been clearly defined in the literature [1]: instead of merely copying natural structures or using biosourced material, one should understand mechanisms behind processes and materials in Nature, since human-made objects and processes do not operate in the same context as natural processes nor with the same goals.
In this contribution we shall revisit the classification of mechanisms underlying nature-inspired engineering proposed in [1], namely hierarchical transport network, force balancing and dynamic self-organization. In the light of nonequilibrium thermodynamics (NET) and of the constructal law (CL), we shall first consider any chemical system as an open system undergoing processes and evidence that the three above mechanisms refer to NET and CL concepts.
We shall also show that more NET and CL concepts could be exploited to design, build and operate nature-inspired chemical engineering processes. This could foster a great potential of innovation, in particular at the unit operation scale and at the chemical plant scale.

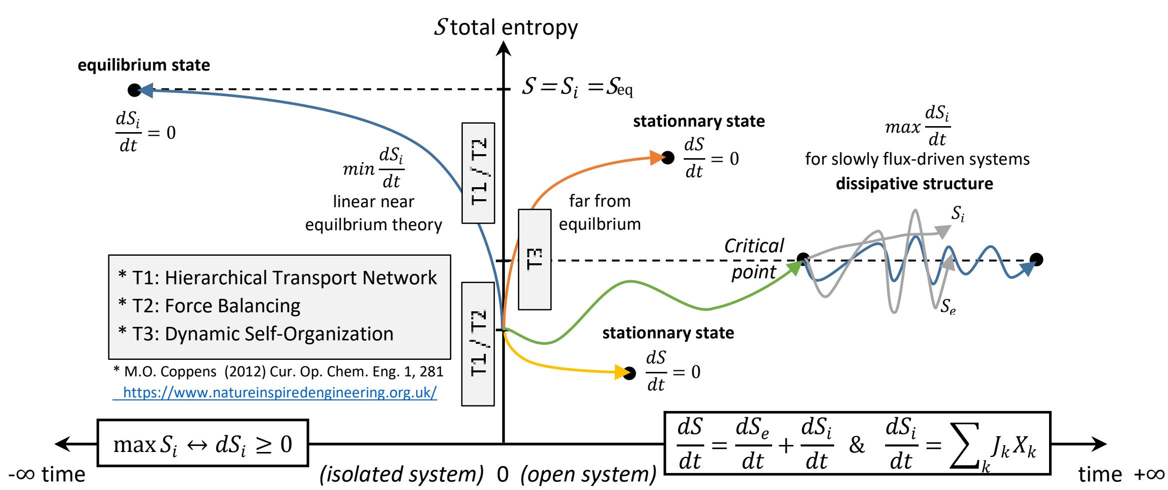

Figure 6 – Nonequilibrium perspective of nature inspired mechanisms

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DISCOVERY, APPLICATIONS AND SCALE-UP OF BIOINSPIRED NANOMATERIALS

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Key Words: Scalable Manufacturing of Nanomaterials; Biomedical & Healthcare Engineering; Energy & Environmental Technology.

Inorganic nanomaterials are widely used in industry and in consumer products with a global production of the order of several million tons per annum and worth several $billions. Current methods for nanomaterials synthesis or manufacturing suffer from significant environmental burden leading to high costs and unsustainable production. In contrast, biological organisms, through biomineralisation, produce elaborate and ordered nanomaterials under physiological conditions. Learning from organisms, we have developed green nanomaterials (GN) synthesis (Figure 1).[1] This green method (mild, one-pot and rapid synthesis in water, at room temperature and neutral pH) offers substantial reductions in resources, time and energy usage when compared to traditional routes, yet offers excellent control over the properties and function of the materials. This presentation will illustrate how key synthetic parameters were identified systematically using Design of Experiments in order to modulate silica formation, its physicochemical properties and its function. Furthermore, experimental results and techno-economic analysis of manufacturing using this new process will be discussed.[2-4] This includes our systematic approach in terms of both process scale-up and process intensification. These results suggested that the process operates well in both batch and continuous mode in tank and tubular reactors. We have also focused on some aspects of downstream processing, in particular, purification of the products, allowing a complete removal of organics, with an added possibility of composition and porosity control. Given that this is a non-destructive method, >90% water and additive can be recycled, further improving the sustainability and economics.[4]

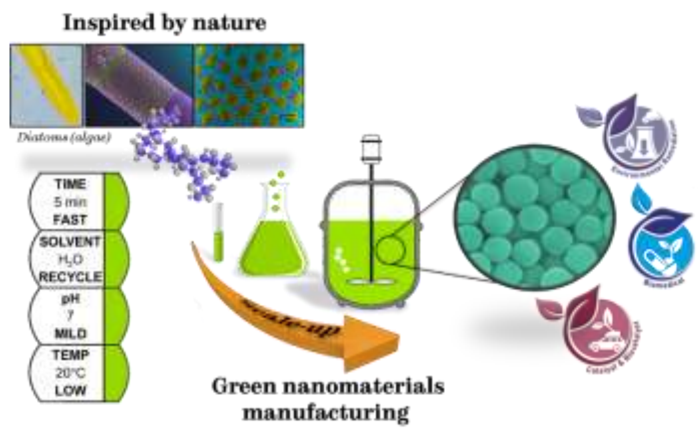

Figure 7 – An overview of the bioinspired approach taken for developing green nanomaterials. Image reproduced from ref. 1.

We are developing green nanomaterials for a wide variety of applications (e.g. energy storage,[5] carbon capture & sequestration,[6] environmental remediation,[7] biocatalysis[8] and drug delivery[9]). This presentation will conclude by summarising how bioinspired routes can help design sustainable manufacturing technologies for high value nanomaterials and identifying future challenges and focus areas.

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INFLUENCE OF PULSATING FLOW ON DISPERSION IN HELICALLY COILED TUBES AND COILED FLOW INVERTERS

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Key Words: Residence Time Distribution, Oscillatory Flow, Tube Curvature

Narrow Residence Time Distribution (RTD) is a desirable characteristic for many chemical engineering processes. However, when flow devices operate at low Reynolds number (characteristic for micro and millifluidic devices), significant fluid dispersion can occur. Narrowing RTD, while maintaining long space time, is currently a challenge. In this work, we addressed this by a combination of passive and active mixing techniques similar to those found in arterial flow. In the biomedical literature, plug flow is often assumed due to low axial dispersion in blood flow [1]. By reviewing this literature, we identified that the reduction in axial dispersion in arteries can be attributed to two factors, curvature of the blood vessels (Dean number in arteries reaches 260) [2] and pulsation of the flow [3]. Flow in curved geometries leads to formation of Dean vortices due to centrifugal force and is a well-established passive mixing technique [4]. At the same time, the introduction of a periodic variation in the flow rate (later on referred to as pulsation for simplicity) is an active technique which was first described in the fluid dynamics literature in the early 1960s [5]; however, it is yet to be utilized to its full potential within the millifluidic community. In process engineering, each of these techniques has been shown separately to have a positive effect and here we investigate the effect of utilizing both of these techniques simultaneously for narrowing RTD. The effect of two key dimensionless pulsation parameters, amplitude ratio (α, dimensionless amplitude of pulsation) and Strouhal Number (St, dimensionless frequency of pulsation), on RTDs was studied in Helically Coiled Tubes (HCTs) and Coiled Flow Inverters (CFIs). Additionally, the contribution of tube elasticity was also considered, since arteries are less rigid than the hard walled channels typically used in chemical engineering processes.

An experimental system was developed to conduct RTD experiments via step injection of tracer at the tube inlet and measurement of tracer concentration via UV-Vis spectroscopy at the tube outlet. Experiments without pulsation were also conducted for comparison. The results showed that in the presence of pulsation narrower RTDs are achievable. Furthermore, both increase in amplitude and frequency of pulsation have a positive effect on reducing dispersion. Separately, pulsation and curved geometries could achieve a maximum reduction of vessel dispersion number (dimensionless parameter that measures the extent of axial dispersion) from 190 to 110 and 125, respectively. When tube curvature and flow pulsation are combined, the vessel dispersion number was reduced by an order of magnitude (from 190 to 20). Numerical simulations supported the experimental results and showed that in the presence of pulsation there is a significant enhancement of radial mixing. Further consideration included the effect of tube elasticity on RTD. It was found that reduction in the RTD width in a harder material is more pronounced than that in a softer material. Overall, the results show a promising technique for reducing the RTD, which can benefit a variety of fields including process intensification, particle synthesis and continuous manufacturing.

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PROCESS INTENSIFICATION AND PROCESS SCALE-UP: GAPS AND OPPORTUNITIES

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Keywords: Process intensification, scale-up, number-up

Process intensification (PI) has gained traction in modern chemical engineering and process technology with its potential for drastic improvements in equipment size, efficiency and carbon footprint. Technologies that exert greater control of process fluid dynamics, heat and mass transfer, and reaction kinetics offer the ability to achieve step changes in performance over conventional technology. Process intensification has already found commercial success exploiting these phenomena in niche separations and reactions, prominently in the area of specialty chemicals and products.

In large-scale industrial processes such as refining and commodity chemicals, effective process scale-up is required to capture economies of scale for large production volumes. The current paradigm for rapid scale-up uses small-scale studies to decouple the relevant process physics and use models to integrate these physical effects for confident commercial design. Translating this paradigm presents challenges and opportunities for process intensification to address. The complex and closely-coupled physics in PI technologies (e.g., dynamic absorption) require deeper understanding than conventional technologies in order to scale up with confidence. This physical coupling may require larger process demonstration testing that significantly increases development time and cost relative to conventional technologies.

This paper will present an assessment of the unique challenges for scale-up of PI technologies addressing both the technical complexity of scale-up as well as the applicability for large-scale commodity processes. Where scale limitations of current PI technologies exist, it highlights tradeoffs between scale-up and “number-up” approaches to commercial design. The authors will present examples to illustrate these opportunities, including commodity processing areas where new PI solutions are still needed (e.g., solids handling, bio-processes).

BIO-INSPIRED OPTICS: LIQUID LENSES IMITATING EYE REFLEXES

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Key Words: liquid lenses, optofluidics, biomimetic optics, lasers.

Biological vision systems such as animals or insects eye exhibit simplicity and multiplicity of operational characteristics that are not available to the traditional optical technologies. The distinctive features of the visual organs of living species allowing the adaptation for the environment using visual-motor reactions, inspired researchers to develop numerous biomimetic compact optical devices [1-4]. We demonstrate a laser controlled liquid-based tunable optical system replicating the eye behavior including the accommodation, the pupillary light response and the optokinetic response. A liquid droplet serving as a multifunctional lens consist of the mixture of tensioactive liquid and volatile liquid with low surface tension. The actuation principle is based on action of thermocapillary and solutocapillary forces generated by a thermal action of the laser beam. The laser heating lowers the fraction of volatile liquid resulting in an increase in surface tension. The increase in the laser power leads to a shrinkage of the droplet and consequently to the increase of the surface curvature. The decrease in the power results in a spreading of the droplet and hence to the decrease of the curvature. This behavior of the droplet is similar to the eye accommodation reflex and the pupillary light reflex in response to the intensity of light. To validate the proposed concept ethylene glycol/isopropyl alcohol mixture dyed with methyl violet for absorption of the laser radiation (532 nm) were used. The volume of mixture (2 microliter) was placed in a sealed optically transparent microcell. Fig. 1(a) shows variation of the focal length and the aperture (images) of the droplet in response to the laser power variation. Over the range of laser power from 2 to 30 mW the focal length changed from 40 to 15 mm. The droplet curvature changing with the supplied power is shown in Fig. 1(b). The focus adjustment time in response to the laser power changing layes from hundreds ms to a few seconds. Fig 1(c) shows an ability the droplet to move on the substrate toward a new position of the laser beam that replicates the optokinetic response of the eye. Speed of the droplet motion reaches 100 µm/s.

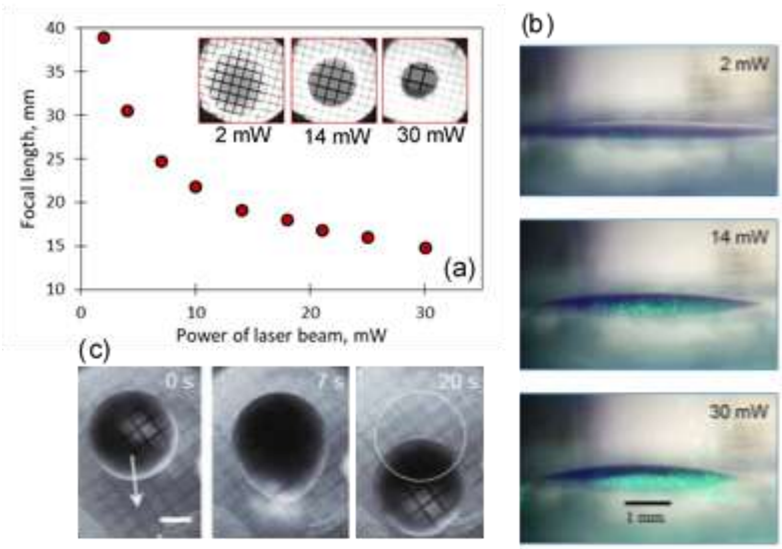

Figure 8 – (a) The droplet focal length variation vs. the laser power (images of a test-grid obtained with the droplet-lens); (b) the droplet reshaping vs. the laser power [5]; (c) The droplet motion to a new position of the laser beam [5]. Dashed circle shows the previous position of the droplet. Scale bar, 1 mm.

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BIOINSPIRED MICRO/NANOSTRUCTURED SURFACES WITH WETTABILITY FROM DESIGN TO FUNCTIONS

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Key Words: Bioinspired, Micro- and nanostructure, wettability, water collection, water repellency.

Biological surfaces provide endless inspiration for design and fabrication of smart materials. It has recently been revealed to have become a hot research area in materials and science world. For instance, the capture silk of the cribellate spider Uloborus walckenaerius collects water through a combination of multiple gradients in a periodic spindle-knot structure after rebuilding. Inspired by the roles of micro- and nanostructures in the water collecting ability of spider silk, a series of bioinspired gradient fibers has been designed by integrating fabrication methods and technologies such as dip-coating, Rayleigh instability break-up droplets, phase separation, strategies of combining electrospinning and electrospraying, and web-assembly. Based on such fabrications above, the “spindle-knot/joint” structures can be tailored to demonstrate the mechanism of multiple gradients (e.g., roughness, smooth, temperature-respond, photo-triggering, etc.,) in driving tiny water drops. A water capturing ability can be developed by the combination of “slope” and “curvature” effects on spindle-knots on bioinspired fiber, including heterostructured fibers to respond environmental humidity, temperature-responsive fiber for directional transport of droplet effectively, multi-geometric gradient fiber for the droplet target transport in a long range along as-designed bioinspired gradient fiber. Otherwise, biological surfaces such as plant leaves and butterfly wings with gradient structure features display the effect of water repellency. Smart bioinspired surfaces can be fabricated by combining machining, electrospinning, soft lithography, and nanotechnology. The gradient surfaces exhibit robust transport and controlling of microdroplets. These bioinspired gradient surfaces would be promising.

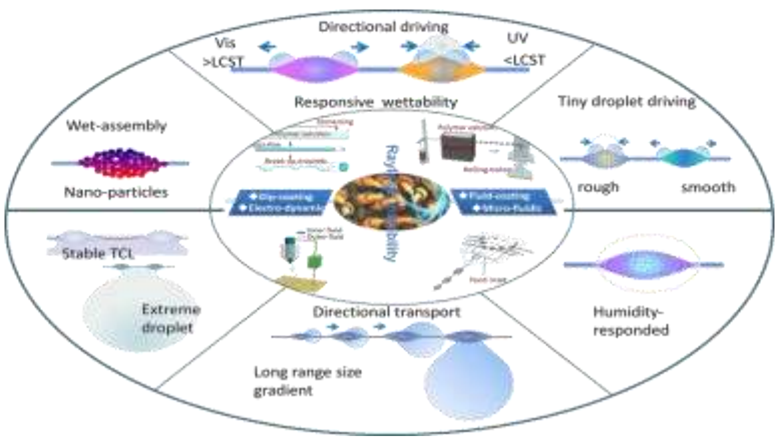

Figure 9 – Bioinspired design and functions of materials

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BIOINSPIRED MATERIALS FOR WATER COLLECTION, WATER PURIFICATION AND OIL-WATER SEPARATION

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Access to a safe supply of water is a human right. However, with growing populations, global warming, and contamination due to human activity, it is one that is increasingly under threat. It is hoped that nature can inspire the creation of materials to aid in the supply and management of water, from water collection and purification to water source clean up and rehabilitation from oil contamination.

Many living species thrive in even the driest places, with some surviving on water harvested from fog[1,2,3]. Due to temperatures lower than dew point in the deserts at night, water condensation also occurs from ambient[2,3]. By studying living species, new materials can be developed to provide a source of fresh water from fog and condensation for communities across the globe as well as in emergency and defense applications[2,3]. The vast majority of water on Earth is in the oceans. However, current desalination processes are energy intensive. Systems in our own bodies have evolved to transport water efficiently while blocking other molecules and ions. Inspiration can be taken from such to improve the efficiency of desalination and help purify water containing other contaminants[1,2,3]. Finally, oil contamination of water from spills or the fracking technique can result in devastating environmental disasters[1,2]. By studying how natural surfaces interact with liquids, new techniques can be developed to clean up oil-spills and further protect our most precious resource[4].

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WATER-ASSISTED GROWTH OF NANOFLORETS HYBRID NANOSTRUCTURES AND THEIR APPLICATION IN SENSING PLATFORMS

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Key Words: hybrid nanostructures, sensing, nanowires, silicon, germanium.

Self-processing (SP) is typically recognized in the context of biological systems. For example, proteins and RNA molecules undergo SP, which includes chemical and structural modifications.
Recently, we developed a new strategy for the synthesis of metal-semiconductor hybrid nanostructures relying on self-processing mechanism which yield complex hybrid nanostructures in one step by triggering a programmable cascade of events that is autonomously executed. The semiconductor-metal hybrid nanostructures obtained resemble the morphology of grass flowers, termed here Nano-floret. Interestingly, water are used during the 'growth' process of Nano-florets as a mild etchant for synthesis intiation and progression. The synthesis mechanism was directly followed by in situ and ex situ scanning transmission electron microscopy and inductively coupled plasma mass spectrometry analyses. Our results indicate that distinct processing steps including localized oxide etch and metal deposition and process termination can be identified similarly to conventional top-down processing sequences.
The Nano-floret hybrid nanostructures were used for fabrication of sensors featuring a self-forming nanojunction. A main feature of the device is a self-formed nanogap bridging between the Nanofloret (NF) hybrid nanostructures (HNS) and a macroscopic counter-electrode which enables direct detection of molecules and quantum dots, including their electronic fingerprint.

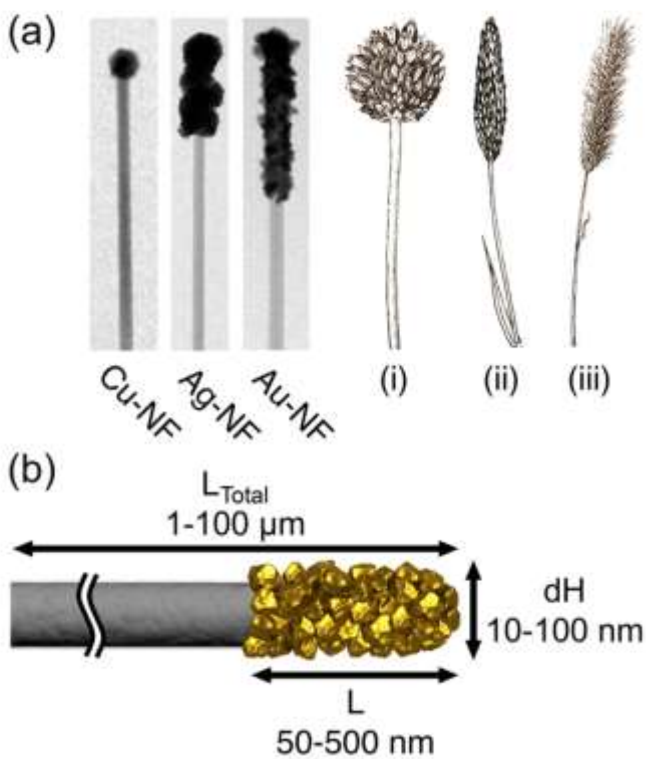
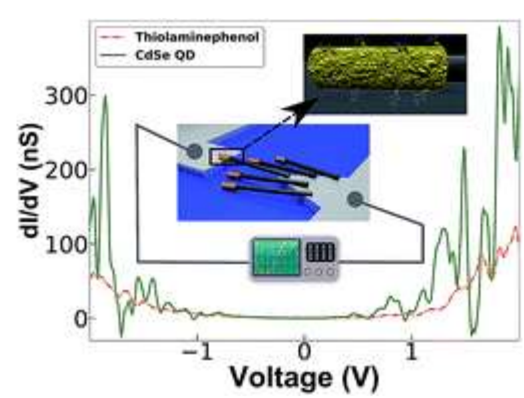


Figure 1. Transmission electron microscopy showing Nano-floret structures (a) obtained for SiGe nanowires reacted with Cu, Ag, and Au featuring a stem and corona (deposited metal) at the tip region. Illustrations of common grass flowers (florets) that resemble the Nano-floret structures obtained for the different metals are shown. (i) Allium scorodoprasum L. subsp. rotundum (L.) Stearn, (ii) Phleum subulatum (Savi) Asche rs. & Graebn., and (iii) Tetrapogon villosus Desf.
(b) Typical dimensions of the Nano-floret components; overall length of 1-100 microns resulting from the SiGe NW used, deposited metal cap is typically 10-100nm in diameter and 50-500 nm long.



MICROFLUIDIC PLATFORM FOR CONTINUOUS SYNTHESIS OF NANOPARTICLES

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Key Words: droplet-based microfluidics; nanoparticles; synthesis; mixing

Nanoparticles of various kind are used in numerous fields of Pharmaceutical and Biomedical Engineering thanks to their unique structural, chemical and physical properties. The common denominator for most high-end applications is the urgent need for nanoparticles with well-defined and uniform properties. For all these applications, particle nucleation and growth control play a significant role due to size and shape-depended properties. Traditionally the batch synthesis method is the most preferred way of nanoparticle preparation for its simplicity and low cost of instrumentation. However, in many instances, it is very challenging to control mixing, heat and mass transport, especially in the case of ultra-fast precipitation reactions and large- volume reaction mixture. This often leads to unwanted batch-to-batch variation in the quality of the product in terms of particle size and shape.

Therefore, better methods are necessary to satisfy annually increasing demands for particles having the monodisperse size and regular shape. Nanoparticle synthesis by microfluidic devices has become one of the most explored methods in the last few years. Microfluidic synthesis promises many advantages over batch synthesis. Firstly, a large surface area to volume ratio of microchannels helps to increase mass and heat transfer in the system. Secondly, it provides higher mixing efficiency using smaller reaction volumes than batch methods. Additionally, microfluidic devices are more suitable to work at harsh conditions in comparison to the batch reactors with regards to rapid temperature and pressure changes while using toxic and explosive materials.

In this work, the synthesis of silica, silver and magnetite nanoparticles will be discussed using the microfluidic platform. The goal was to compare a standard batch process with the continuous process using microfluidics of nanoparticle synthesis. The properties of synthesized nanoparticles, particle size and morphology, will be analyzed and discussed.

BALANCE-OF-FORCE SELECTIVE ACCUMULATION OF TRACE IONIC SPECIES IN HIERARCHICAL SUB-NANO-/NANO-/MICRO-POROUS STRUCTURES

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Key Words: selective accumulation, current-induced salt depletion, trace ion, nanoporous, ion-exchange

Separation of species of close electrochemical mobilities (peptides, isotopes) is of interest for a number of applications. In this presentation, we will explore selective accumulation of ionic species in current-polarized hierarchical sub-nano-/nano-/micro-porous structures.
The selective accumulation of trace ions near micro-/nano-porous interfaces arises from the electric field profile created by transport of the dominant (high-concentration) salt. The dominant-salt counterions (ions with a charge opposite to the immobile charge in the nanoporous membrane) carry a larger fraction of the current in the nanoporous membrane than in the micriopores due to exclusion of coions from the nanopores. Consequently, a salt depletion zone appears next to the membrane (Fig. 1b, black curve) [1], and this depletion gives rise to low electrical conductivity and, hence, a high local electric field (Fig. 1b, red curve). The concentration profile for trace coions is very different than that for the dominant salt and can give remarkable concentration factors that are very sensitive to the trace-coion diffusion coefficient. In Fig. 1, these trace ions (anions in this case) move to the right via electroosmosis-induced convective flow and to the left via Electro-Migration (EM). However, EM of the trace ions increases with the increasing electric field in the dominant-salt depletion region. Thus, if the coion electrical mobility is in the right range, at some position the convective and EM flux components for the trace coions are equal in magnitude and opposite in direction (balance of forces). Near this position trace coions accumulate (Fig. 1b, blue curve) to maintain a steady-state flux that is a combination of convection, EM, and diffusion components [2].

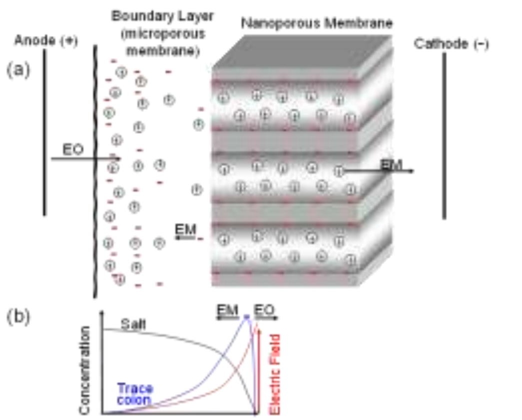

Figure 10 – Schematics of current-induced depletion of micro-/nano-interface and selective accumulation of coions

Figure 2 – Schematics of sandwiched nanoporous and micro-perforated ion-exchange layers

Qualitatively similar phenomena can occur in composite materials comprising an ion-exchange (sub-nanoporous) layer having scarce micro-perforations and juxtaposed with a nanoporous layer as schematically shown in Fig.2 [3]. Current-induced depletion of dominant salt occurs at the interface between non-perforated zones of ion-exchange layer and the nanoporous material. The micro-perforations allow for electroosmotic flow through the system and transport of lower-mobility coions towards the interface. The accumulation occurs close to the latter. In such systems, the effect does not require the use of dilute dominant salts (and, consequently, very dilute trace ions) so its productivity can be higher than in systems sketched in Fig.1. However, the accumulation is less selective. The choice of system will depend on the application and its priorities.

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PH DRIVEN COLLOIDAL TRANSFORMATIONS OF MS2 VIRUS PARTICLES FOR WATER PURIFICATION

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Key Words: pH triggered virus aggregation, bacteriophage MS2, self-assembly, SAXS, cryo-TEM.

Viral infection due to contaminated drinking water is the main cause of infantile death by diarrheal disease [1]. Viruses are difficult to remove by common gravity driven filters due to their nanometer scale size. With the global goal of improving virus removal in drinking water treatments, the colloidal structure of a virus model, MS2 bacteriophage, has been investigated; the effects of pH and Suwannee River natural organic matter in water have been studied [2].

Dynamic light scattering, small angle X-ray scattering and cryogenic transmission electron microscopy were used to characterize the colloidal structure of MS2 in water. The results show that the bacteriophage MS2 is a spherical particle with a core-shell type structure and a total diameter of 27nm. The RNA core has a radius of about 8nm and the protein shell forming the virus capsid is about 6nm thick.

The water pH was discovered to have a major influence on the colloidal structure of the virus: at pH above 5, interparticle repulsions stabilize the virus solution. A decrease in pH to 3 led to diminishing of the repulsion forces and micrometer sized virus aggregates. This aggregation process was reversible upon circulating the water pH. In addition, the presence of Suwannee River natural organic matter that simulates the organic components in surface water was found to sterically stabilize the virus particles, reducing aggregates size and promoting disaggregation with pH increase.
These findings will allow a better understanding of virus interactions and can guide the design of advanced water filtration processes for virus removal.

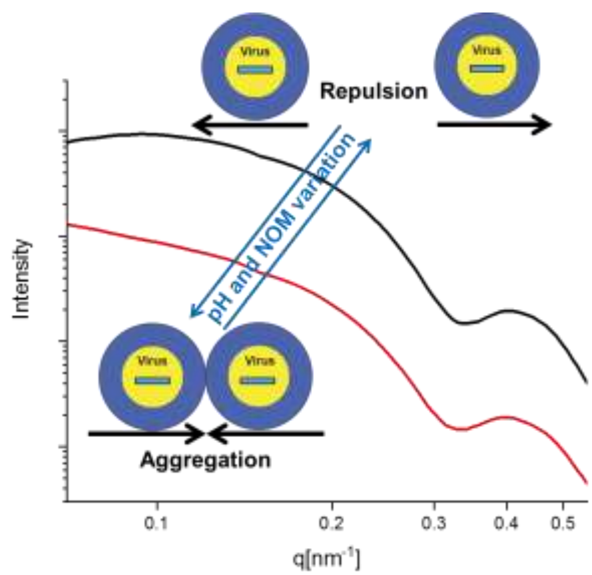

Figure 11 – Water parameters influencing the colloidal state of MS2 bacteriophage from repulsive interactions to aggregation

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DEVELOPMENTAL BIOENGINEERING

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Key Words: Development, Repair, Embryo, Recapitulation, Glia

Among the challenges for nature-inspired engineering is how to build synthetic devices capable of emulating the process of development, and its uses in repair and regeneration. Here, I offer a set of principles for designing and building bio-synthetic self-repairing devices based upon nature's process of development.

First, nature's living devices are built by a process of gene and environment regulated self-organization. I illustrate this principle with the process by which nature builds embryos and discuss how bioengineers are using in vitro organoids to model nature's process. Second, devices are inseparable from the micro-environments in which they develop, as illustrated in nature by the micro-environment of stem cells, called niches, as well as by the regulatory interactions between stem cell and niche. Bioengineers leverage the mechanical and chemical properties of the niche to build synthetic organs, via processes such as bio-printing. A challenge in emulating the way that nature builds organs is the incorporation of vasculature. Third, nature builds consortia of heterogeneous parts that exhibit distributed control, evident in the relation between neurons and glial cells during development of the mammalian nervous system, and in communication between gut bacteria and the brain. Research has demonstrated that manipulating the properties of the gut microbiome influences the brain and may actually change behavior. This may provide leverage for bioengineers in promoting healthy behavior of individuals with neuropathology. Fourth, nature repairs worn-out or damaged parts by recapitulating the developmental processes used to build them. For example, nature uses progenitor, or stem cells, both during development and to repair injured organs. However, not all animals have the same capability for repair and regeneration, as evident in the contrast between salamanders that can regrow a lost limb, and humans who cannot. Bioengineers facing the challenge of repairing human spinal cord injury have made great strides in promoting regeneration by emulating the process in other animals, such as axolotls. Fifth, nature's parts and systems may switch from one function to another, depending upon the context of intrinsic regulatory networks and environmental signals. Glial cells, called microglia, are resident central nervous system immune surveillance cells that have multiple functions during development, including synaptic refinement and clearing dead and dying cells. The detection of changes in a cell's microenvironment may switch microglial function from surveillance to clearance. In diseases such as neurodegeneration, synapses may be incorrectly marked as debris, and activate microglia to eliminate them. It may be possible for bioengineers to program swarms of bio-hybrid molecular robots for similar surveillance functions. Sixth, biological regulatory systems allow animals, such as killifish, to enter altered metabolic states under adverse environmental conditions, such as drought. Synthetic biologists are emulating the processes by which nature enables animals to enter different metabolic states. And seventh, biological systems exhibit emergent properties, such as low-dimensional patterns in the vast connectivity of brain networks as well as in behavior. The appearance of these low dimensional patterns in recordings of animal reaching behavior has implications for control of neuro-prosthetic devices.

DEVELOPMENT OF COMPARTMENTALIZED ANTIBACTERIAL SYSTEMS BASED ON IMMOBILIZED ALLIINASE

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Key Words: garlic, alliinase, enzyme encapsulation, antibacterial activity, spray drying

Multi-drug resistant (MDR) bacteria are one of the most significant threats to modern society. Antibiotics, in the past so effective against broad spectra of infections, are nowadays omnipresent and their widespread availability, misuse and gradual accumulation over time in the environment is the main reason behind the sudden increase of bacterial resistance. However, it has been shown that some natural antibacterial systems are designed in such a way that effectively prevents the development of bacterial resistance.

One of the most known examples of such natural self-defence system is garlic plant, where highly potent but unstable compound allicin is formed enzymatically from inactive precursor (alliin) only when and where the inner cellular structure is compromised (e.g. soil pathogens, rodents). A very short half-time of allicin is the key to garlic’s success: bacteria do not have the necessary time to develop effective countermeasures, and therefore allicin remains ever-lasting natural bactericide for thousands of years compared to relatively stable antibiotics.

In this study, we propose to employ encapsulation techniques (ionic cross-linking, spray drying) to develop polymer carrier where purified and stabilized enzyme (alliinase) and substrate (alliin) are physically separated in two different types of carriers. Additionally, we want to demonstrate the possibility to control the overall rate of enzymatic reaction and allicin generation via the cross-linking ratio (amount of cross-linker per polymer). Finally, the antibacterial effect of prepared carriers will be tested against common bacterial strains using the disc diffusion method and non-contact form of produced allicin in a volatile state.

INSECT-INSPIRED NAVIGATION: SMART TRICKS FROM SMALL BRAINS

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Key Words: Visual navigation, Bio-inspired robotics, Autonomous robotics, Desert ants

Small-brained insects are expert at many tasks that are currently difficult for robots, but especially in the speed and robustness of their learning abilities. In contrast to AI methods which generally take long times to train and large amounts of labelled data, insects are rapid learners of visual and olfactory information and are capable of long distance navigation, exploration and spatial learning. What if we could give robots these abilities, by mimicking the sensors, circuits and behaviours of insects? This is the goal of the Brains on Board project (brainsonboard.co.uk). In this talk, we will discuss the Brains on Board project and our work on insect-inspired visual navigation in particular.

The use of visual information for navigation is a universal strategy for sighted animals, amongst whom ants are particular experts despite have small brains and low-resolution vision [1]. To understand how they achieve this, we combine behavioural experiments with modelling and robotics to show how ants directly acquire and use task-specific information through specialised sensors, brains and behaviours, enabling complex behaviour to emerge without complex processing. In this spirit, we will show that an agent – insect or robot – can robustly navigate without ever knowing where it is, without specifying when or what it should learn, nor requiring it to recognise specific objects, places routes or maps. This leads to an algorithm in which visual information specifies actions not locations in which route navigation is recast as a search for familiar views allowing routes through visually complex worlds to be encoded by a single layer artificial neural network (ANN) after a single training run with only low resolution vision [2]. As well as meaning that the algorithms are plausible in terms of memory load and computation for a small-brained insect, it also makes them very well-suited to a small, power-efficient, robot.

We thus demonstrate that this algorithm, with all computation performed on a small low-power robot, is capable of delivering reliable direction information along outdoor routes, even when scenes contain few local landmarks and have high-levels of noise (from variable lighting and terrain) [3]. Indeed, routes can be precisely recapitulated and we show that the required computation does not increase with the number of training views. Thus the ANN provides a compact representation of the knowledge needed to traverse a route. In fact, rather than the compact representation losing information, there are instances where the use of an ANN ameliorates the problems of sub optimal paths caused by tortuous training routes. Our results suggest the feasibility of familiarity-based navigation for long-range autonomous visual homing.

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NATURE-INSPIRED ROBOTICS FOR PHYSICAL INTERACTION WITH THE WORLD

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Key Words: Robotics, bioinspiration, soft materials

As we bring robots out of the laboratory and into the world at large, one of the most important lessons we can learn from nature is how not only to tolerate but to exploit physical interactions with the environment. Examples of robots that need to take advantage of surface interactions include multimodal flying/climbing robots, adhesive microrobots that can pull loads, and robots that grasp and manipulate objects or surfaces using arrays of insect-inspired microspines or gecko-inspired adhesives. In each case, these robots have prompted collaborations with biologists and materials scientists to develop new materials and structures that exploit interactions in the environment. Nature offers many examples of structures and functional materials that help to manage these interactions. Investigations of them also allow us to discover new opportunities for synergy when combining multiple locomotion modes (e.g., flying and climbing).

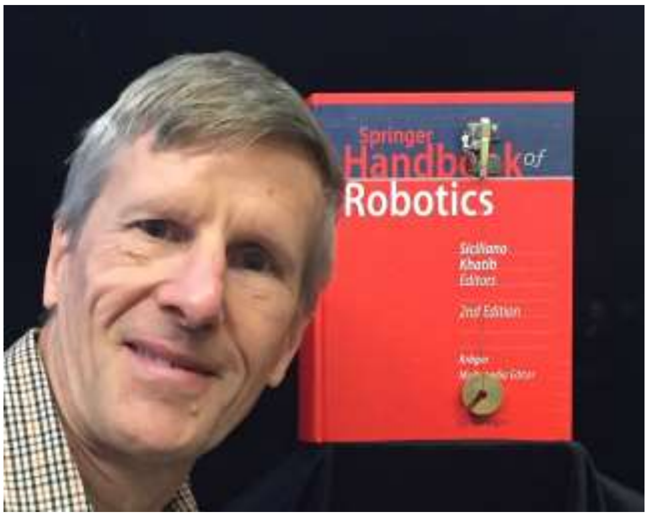

Figure 12. An adhesive microbot pulls a weight while climbing a vertical surface.

As the new nature-inspired robots are developed and tested, dynamic models lead to computed “envelopes” of conditions for which the robot is expected to perform reliably – for example, to latch onto a surface without slipping or bouncing off. As contact takes place, the dynamics are typically fast, so that passive properties of mechanisms are more effective than closed-loop control to dissipate energy, distribute forces and stabilize the robot. The results of these models and experiments can provide insight for biologists as well as engineers. They allow both communities to test hypotheses about which effects or principles are most important for successful operation.