Joanna Aizenberg

Co-Director of The Kavli Institute at Harvard University

Amy Smith Berylson Professor of Materials Science

School of Engineering and Applied Sciences

The Aizenberg lab's research is aimed at understanding some of the basic principles of biological architectures and the economy with which biology solves complex problems in the design of multifunctional, adaptive materials. The goal is to use biological principles as guidance in developing new, bio-inspired synthetic routes and nanofabrication strategies that would lead to advanced materials and devices, with broad impact in fields ranging from architecture to energy efficiency to medicine.

The lab pursues a wide range of research interests that include biomineralization, self-adapting materials, slippery omniphobic surfaces, bio-inspired optics, colloidal self-assembly, selective surface wettability, nanofabrication, and bio-nano interfaces.

List of papers acknowledging the Kavli Foundation with abstracts appended

I.B. Burgess, J. Aizenberg, M. Loncar, "Creating Bio-inspired 3D-2D Photonic Stacks via Planar Lithography on Self-assembled Inverse-opals," Bioinspir. Biomim., 2013, 8, 045004 [Invited].

> Structural hierarchy and complex 3D architecture are characteristics of biological photonic designs that are challenging to reproduce in synthetic materials. Top-down lithography allows for designer patterning of arbitrary shapes, but is largely restricted to planar 2D structures. Self-assembly techniques facilitate easy fabrication of 3D photonic crystals, but controllable defect-integration is difficult. In this paper we combine the advantages of top-down and bottom- up fabrication, developing two techniques to deposit 2D-lithographically-patterned planar layers on top of or in between inverse-opal 3D photonic crystals and creating hierarchical structures that resemble the architecture of the bright green wing scales of the butterfly, *Parides sesostris*. These fabrication procedures, combining advantages of both top-down and bottom-up fabrication, may prove useful in the development of omnidirectional coloration elements and 3D-2D photonic crystal devices.

B. D. Hatton, I. Wheeldon, M. J. Hancock, M. Kolle, J. Aizenberg, D. E. Ingber, "An Artificial Vasculature for Adaptive Thermal Control of Windows," Solar Energy Materials and Solar Cells, 2013, 117, 429-436.

> Windows are a major source of energy inefficiency in buildings. In addition, heating by thermal radiation reduces the efficiency of photovoltaic panels. To help reduce heating by solar absorption in both of these cases, we developed a thin, transparent, bio-inspired, convective cooling layer for building windows and solar panels that contains microvasculature

with millimeter-scale, fluid-filled channels. The thin cooling layer is composed of optically clear silicone rubber with microchannels fabricated using microfluidic engineering principles. Infrared imaging was used to measure cooling rates as a function of flow rate and water temperature. In these experiments, flowing room temperature water at 2 mL/min reduced the average temperature of a model 10 10 cm2 window by approximately 7–9 1C. An analytic steady-state heat transfer model was developed to augment the experiments and make more general estimates as functions of window size, channel geometry, flow rate, and water temperature. Thin cooling layers may be added to one or more panes in multi-pane windows or as thin film non-structural central layers. Lastly, the color, optical transparency and aesthetics of the windows could be modulated by flowing different fluids that differ in their scattering or absorption properties.

A.K. Epstein, D. Hong, P. Kim, J. Aizenberg, "Biofilm Attachment Reduction on Bioinspired, Dynamic, Micro-wrinkling Surfaces", New J. Physics, 2013, 15, 095018,DOI:10.1088/1367 2630/15/9/095018.

Most bacteria live in multicellular communities known as biofilms that are adherent to surfaces in our environment, from sea beds to plumbing sys- tems. Biofilms are often associated with clinical infections, nosocomial deaths and industrial damage such as bio-corrosion and clogging of pipes. As mature biofilms are extremely challenging to eradicate once formed, prevention is ad- vantageous over treatment. However, conventional surface chemistry strategies are either generally transient, due to chemical masking, or toxic, as in the case of leaching marine antifouling paints. Inspired by the nonfouling skins of echino- derms and other marine organisms, which possess highly dynamic surface struc- tures that mechanically frustrate bio-attachment, we have developed and tested a synthetic platform based on both uniaxial mechanical strain and buckling- induced elastomer microtopography. Bacterial biofilm attachment to the dynamic substrates was studied under an array of parameters, including strain amplitude and timescale (1–100 mm s–1), surface wrinkle length scale, bacterial species and cell geometry, and growth time. The optimal conditions for achieving up to ~80% *Pseudomonas aeruginosa* biofilm reduction after 24 h growth and ~60% reduction after 48 h were combinatorially elucidated to occur at 20% strain am- plitude, a timescale of less than ~5 min between strain cycles and a topogra- phy length scale corresponding to the cell dimension of ~1 μm. Divergent ef- fects on the attachment of *P. aeruginosa*, *Staphylococcus aureus* and *Escherichia coli* biofilms showed that the dynamic substrate also provides a new means of species-specific biofilm inhibition, or inversely, selection for a desired type of bacteria, without reliance on any toxic or transient surface chemical treatments.

J. Aizenberg, P. Fratzl, "New Materials Through Bioinspiration and Nanoscience", Adv. Funct. Mater., 2013, 23, 4398-4399.

(no abstract)

L. Mishchenko, J. Aizenberg, B. Hatton, "Spatial Control of Condensation and Freezing on Superhydrophobic Surfaces with Hydrophilic Patches, Adv. Funct. Mater., 2013, 23, 4577-4584;

DOI: 10.1002/adfm.201300418.

Certain natural organisms use micro-patterned surface chemistry, or ice- nucleating species, to control water condensation and ice nucleation for survival under extreme conditions. As an analogy to these biological approaches, it is shown that functionalized, hydrophilic polymers and particles deposited on the tips of superhydrophobic posts induce precise topographical control over water condensation and freezing at the micrometer scale. A bottom-up deposition process is used to take advantage of the limited contact area of a non-wetting aqueous solution on a superhydrophobic surface. Hydrophilic polymer deposition on the tips of these geometrical structures allows spatial control over the nucleation, growth, and coalescence of micrometer-scale water droplets. The hydrophilic tips nucleate water droplets with extremely uniform nucleation and growth rates, uniform sizes, an increased stability against coalescence, and asymmetric droplet morphologies. Control of freezing behavior is also demonstrated via deposition of ice-nucleating AgI nanoparticles on the tips of these structures. This combination of the hydro- philic polymer and AgI particles on the tips was used to achieve templating of ice nucleation at the micrometer scale. Preliminary results indicate that control over ice crystal size, spatial symmetry, and position might be possible with this method. This type of approach can serve as a platform for system- atically analyzing micrometer-scale condensation and freezing phenomena, and as a model for natural systems.

M. A. Kats, S. Byrnes, R. Blanchard, M. Kolle, P. Genevet, J. Aizenberg, F. Capasso, “Enhancement of Absorption and Color Contrast in Ultra-thin Highly-absorbing Optical Coatings”, Appl. Phys. Lett. 2013, 103, 101104.

Recently a new class of optical interference coatings was introduced which comprises ultra-thin, highly absorbing dielectric layers on metal substrates. We show that these lossy coatings can be augmented by an additional transparent subwavelength layer. We fabricated a sample comprising a gold substrate, an ultra-thin film of germanium with a thickness gradient, and several alumina films. The experimental reflectivity spectra showed that the additional alumina layer increases the color range that can be obtained, in agreement with calculations. More generally, this transparent layer can be used to enhance optical absorption, protect against erosion, or as a transparent electrode for optoelectronic devices.

N. Vogel, R. Belisle, B. Hatton, T.-S. Wong, J. Aizenberg, “Transparency, Damage Tolerance and Patternability of Omniphobic Lubricated Surfaces Based on Inverse Colloidal Monolayers”, Nat. Commun., 2013, 4, 2167, DOI: 10.1038/ncomms3176.

A transparent coating that repels a wide variety of liquids, prevents staining, is capable of self-repair and is robust towards mechanical damage can have a broad technological impact, from solar cell coatings to self-cleaning optical devices. Here we employ colloidal templating to design transparent, nanoporous surface structures. A lubricant can be firmly locked into the structures and, owing to its fluidic nature, forms a defect-free, self-healing interface that eliminates the pinning of a second liquid applied to its surface, leading to efficient liquid repellency, prevention of adsorption of liquid-borne contaminants, and reduction of ice

adhesion strength. We further show how this method can be applied to locally pattern the repellent character of the substrate, thus opening opportunities to spatially confine any simple or complex fluids. The coating is highly defect-tolerant due to its interconnected, honeycomb wall structure, and repellency prevails after the application of strong shear forces and mechanical damage. The regularity of the coating allows us to understand and predict the stability or failure of repellency as a function of lubricant layer thickness and defect distribution based on a simple geometric model.

S. H. Kang, S. Shan, W. L. Noorduin, M. Khan, J. Aizenberg, K. Bertoldi, “Buckling-induced Reversible Symmetry Breaking and Amplification of Chirality using Supported Cellular Structures," Adv. Mater., 2013, 25, 3380-3385.

Buckling-induced reversible symmetry breaking and amplification of chirality using macro- and microscale supported cellular structures is described. Guided by extensive theoretical analysis, cellular structures are rationally designed, in which buckling induces a reversible switching between achiral and chiral configurations. Additionally, it is demonstrated that the proposed mechanism can be generalized over a wide range of length scales, geometries, materials, and stimuli.

D. Daniel, M. N. Mankin, R. Belisle, T.-S. Wong, “Lubricant-Infused Micro/Nano-structured Surfaces with Tunable Dynamic Omniphobicity at High Temperatures," App. Phy. Lett., 2013, 102, 231603, DOI: 10.1063/1.4810907.

Omniphobic surfaces that can repel fluids at temperatures higher than 100□C are rare. Most state- of-the-art liquid-repellent materials are based on the lotus effect, where a thin air layer is maintained throughout micro/nanotextures leading to high mobility of liquids. However, such behavior eventually fails at elevated temperatures when the surface tension of test liquids decreases significantly. Here, we demonstrate a class of lubricant-infused structured surfaces that can maintain a robust omniphobic state even for low-surface-tension liquids at temperatures up to at least 200 C. We also demonstrate how liquid mobility on such surfaces can be tuned by a factor of 1000.

X. Yao, Y. Hu, A. Grinthal, T.-S. Wong, L. Mahadevan, J. Aizenberg, “Adaptive Fluid-infused Porous Films with Tunable Transparency and Wettability," Nature Mater., 2013, 12, 529-534.

Materials that adapt dynamically to environmental changes are currently limited to two-state switching of single properties, and only a small number of strategies that may lead to materials with continuously adjustable characteristics have been reported1–3. Here we introduce adaptive surfaces made of a liquid film supported by a nanoporous elastic substrate. As the substrate deforms, the liquid flows within the pores, causing the smooth and defect-free surface to roughen through a continuous range of topographies. We show that a graded mechanical stimulus can be directly translated into finely tuned, dynamic adjustments of optical transparency and wettability. In particular, we demonstrate simultaneous control of the film’s transparency and its ability to continuously manipulate various low-surface-tension

droplets from free- sliding to pinned. This strategy should make possible the rational design of tunable, multifunctional adaptive materials for a broad range of applications.

W. L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, “Rationally Designed Complex Hierarchical Microarchitectures,” Science, 2013, 340, 832-837.

The emergence of complex nano- and microstructures is of fundamental interest, and the ability to program their form has practical ramifications in fields such as optics, catalysis, and electronics. We developed carbonate-silica microstructures in a dynamic reaction-diffusion system that allow us to rationally devise schemes for precisely sculpting a great variety of elementary shapes by diffusion of carbon dioxide (CO_2) in a solution of barium chloride and sodium metasilicate. We identify two distinct growth modes and show how continuous and discrete modulations in CO_2 concentration, pH, and temperature can be used to deterministically switch between different regimes and create a bouquet of hierarchically assembled multiscale microstructures with unprecedented levels of complexity and precision. These results outline a nanotechnology strategy for “collaborating” with self-assembly processes in real time to build arbitrary tectonic architectures.

P. Kim, Y. Hu, J. Alvarenga, M. Kolle, Z. Suo, J. Aizenberg, “Rational Design of Mechano Responsive Optical Materials by Fine Tuning the Evolution of Strain-Dependent Wrinkling Patterns,” Adv. Opt. Mat., 2013, 381-388, DOI: 10.1002/adom.201300034.

Rational design strategies for mechano-responsive optical material systems are created by introducing a simple experimental system that can continu- ously vary the state of bi-axial stress to induce various wrinkling patterns, including stripes, labyrinths, herringbones, and rarely observed checker- boards, that can dynamically tune the optical properties. In particular, a switching of two orthogonally oriented stripe wrinkle patterns from oxidized polydimethylsiloxane around the critical strain value is reported, as well as the coexistence of these wrinkles forming elusive checkerboard patterns, which are predicted only in previous simulations. These strain-induced wrinkle patterns give rise to dynamic changes in optical transmittance and diffraction patterns. A theoretical description of the observed pattern forma- tion is presented which accounts for the residual stress in the membrane and allows for the fine-tuning of the window of switching of the orthogonal wrinkles. Applications of wrinkle-induced changes in optical properties are demonstrated, including a mechanically responsive instantaneous privacy screen and a transparent sheet that reversibly reveals a message or graphic and dynamically switches the transmittance when stretched and released.

P. Kim, J. Alvarenga, J. Aizenberg, R. S. Sleeper, “Hydroglyphics: Demonstration of Selective Wetting on Hydrophilic and Hydrophobic Surface," J. Chem. Ed., 2013, 90, 625-628, DOI: 10.1021/ed3003308.

A visual demonstration of the difference between hydrophilic and hydrophobic surfaces has been developed. It involves placing a shadow mask on an optically clear hydrophobic plastic dish, corona treating the surface with a modified Tesla coil, removing the shadow mask, and

visualizing the otherwise invisible message or pattern by applying water, thus entitled as hydroglyphics.

T.-S. Wong, T. Sun, L. Feng, J. Aizenberg, "Interfacial Materials with Special Wettability," MRS Bull., 2013, 38, 366-371.

Various life forms in nature display a high level of adaptability to their environments through the use of sophisticated material interfaces. This is exemplified by numerous biological systems, such as the self-cleaning of lotus leaves, the water-walking abilities of water striders and spiders, the ultra-slipperiness of pitcher plants, the directional liquid adhesion of butterfly wings, and the water collection capabilities of beetles, spider webs, and cacti. The versatile interactions of these natural surfaces with fluids, or special wettability, are enabled by their unique micro/nanoscale surface structures and intrinsic material properties. Many of these biological designs and principles have inspired new classes of functional interfacial materials, which have remarkable potential to solve some of the engineering challenges for industrial and biomedical applications. In this article, we provide a snapshot of the state of the art of biologically inspired materials with special wettability, and discuss some promising future directions for the field.

M. Kolle, A. Lethbridge, M. Kreysing, J. J. Baumberg, J. Aizenberg, P. Vukusic, "Bio-inspired Band-gap Tunable Elastic Optical Multilayer Fibers," Adv. Mater., 2013, 25, 2239-2245, DOI:10.1002/adma.201203529.

The concentrically-layered photonic structure found in the tropical fruit *Margaritaria nobilis* serves as inspiration for photonic fibers with mechanically tunable band-gap. The fibers show the spectral filtering capabilities of a planar Bragg stack while the microscopic curvature decreases the strong directional chromaticity associated with flat multilayers. Elongation of the elastic fibers results in a shift of the reflection of over 200 nm.

R. S. Friedlander, H. Vlamakis, P. Kim, M. Khan, R. Kolter, J. Aizenberg, "Bacterial Flagella Explore Micro-scale Hummocks and Hollows to Increase Adhesion," PNAS, 2013, 110(14), 5624 5629.

Biofilms, surface-bound communities of microbes, are economi- cally and medically important due to their pathogenic and ob- structive properties. Among the numerous strategies to prevent bacterial adhesion and subsequent biofilm formation, surface topography was recently proposed as a highly nonspecific method that does not rely on small-molecule antibacterial compounds, which promote resistance. Here, we provide a detailed investiga- tion of how the introduction of submicrometer crevices to a surface affects attachment of Escherichia coli. These crevices reduce substrate surface area available to the cell body but increase overall surface area. We have found that, during the first 2 h, adhesion to topographic surfaces is significantly reduced compared with flat controls, but this behavior abruptly reverses to significantly in- creased adhesion at longer exposures. We show that this reversal coincides with bacterially induced wetting transitions and that flagellar filaments aid in adhesion to

these wetted topographic surfaces. We demonstrate that flagella are able to reach into crevices, access additional surface area, and produce a dense, fibrous network. Mutants lacking flagella show comparatively reduced adhesion. By varying substrate crevice sizes, we determine the conditions under which having flagella is most advantageous for adhesion. These findings strongly indicate that, in addition to their role in swimming motility, flagella are involved in attach- ment and can furthermore act as structural elements, enabling bacteria to overcome unfavorable surface topographies. This work contributes insights for the future design of antifouling surfaces and for improved understanding of bacterial behavior in native, structured environments.

P. Kim, M. J. Kreder, J. Alvarenga, J. Aizenberg, “Hierarchical or Not? Effect of the Length Scale and Hierarchy of the Surface Roughness on Omniphobicity of Lubricant-infused Substrates,” Nano Lett., 2013, 13(4), 1793-1799.

Lubricant-infused textured solid substrates are gaining remark- able interest as a new class of omni-repellent nonfouling materials and surface coatings. We investigated the effect of the length scale and hierarchy of the surface topography of the underlying substrates on their ability to retain the lubricant under high shear conditions, which is important for maintaining nonwetting properties under application-relevant conditions. By comparing the lubricant loss, contact angle hysteresis, and sliding angles for water and ethanol droplets on flat, microscale, nanoscale, and hierarchically textured surfaces subjected to various spinning rates (from 100 to 10 000 rpm), we show that lubricant-infused textured surfaces with uniform nanofeatures provide the most shear-tolerant liquid-repellent behavior, unlike lotus leaf-inspired superhydrophobic surfaces, which generally favor hierarchical structures for improved pressure stability and low contact angle hysteresis. On the basis of these findings, we present generalized, low-cost, and scalable methods to manufacture uniform or regionally patterned nanotextured coatings on arbitrary materials and complex shapes. After functionalization and lubrication, these coatings show robust, shear-tolerant omniphobic behavior, transparency, and nonfouling properties against highly contaminating media.

X. He, R. S. Friedlander, L. D. Zarzar, J. Aizenberg, “Chemo-Mechanically Regulated Oscillation of an Enzymatic Reaction," Chem. Mat., 2013, 25(4), 521-523.

(no abstract)

I. B. Burgess, M. Loncar, J. Aizenberg, “Structural Colour in Colourimetric Sensors and Indicators”, Journal of Materials Chemistry C, 1, 6075-6086 [Invited].

Colourimetric sensors and indicators are widely used because of their low cost and simplicity. A significant challenge associated with the design of this type of device is that the sensing mechanism must be simultaneously optimised for the sensitivity of the response and a visually perceptible colour change. Structural colour, derived from coherent scattering rather than molecular absorption, is a promising route to colourimetric sensor design because colour shifts are tied to changes in one of many physical properties of a material, rather than a specific chemical process. This Feature Article presents an overview of the development of low-cost sensors and indicators that exploit structural colour. Building upon recent advances

in structurally adaptive materials design, structural colour sensors have been developed for a wide variety of previously inaccessible physical (e.g. temperature, strain, electric fields) and chemical stimuli (e.g. small organic molecules, charged species, biomacromolecules and metabolites). These devices, often exceeding the state of the art in performance, simplicity or both, have bright prospects for market impact in areas such as environmental monitoring, workplace hazard identification, threat detection, and point-of-care diagnostics. Finding the ideal balance between performance (e.g. sensitivity, specificity, reproducibility, etc.) and simplicity (e.g. colourimetric vs. spectroscopic readout) will be one of the most critical elements in the further development of structural colour sensors. This balance should be driven largely by the market demands and competing technologies.

A. Grinthal and J. Aizenberg, “Adaptive All the Way Down: Building Responsive Materials from Hierarchies of Chemomechanical Feedback,” Chem. Soc. Rev. 2013, 42, 7072-7085 [Invited].

A living organism is a bundle of dynamic, integrated adaptive processes: not only does it continuously respond to constant changes in temperature, sunlight, nutrients, and other features of its environment, but it does so by coordinating hierarchies of feedback among cells, tissues, organs, and networks all continuously adapting to each other. At the root of it all is one of the most fundamental adaptive processes: the constant tug of war between chemistry and mechanics that interweaves chemical signals with endless reconfigurations of macromolecules, fibers, meshworks, and membranes. In this tutorial we explore how such chemomechanical feedback – as an inherently dynamic, iterative process connecting size and time scales – can and has been similarly evoked in synthetic materials to produce a fascinating diversity of complex multiscale responsive behaviors. We discuss how chemical kinetics and architecture can be designed to generate stimulus-induced 3D spatiotemporal waves and topographic patterns within a single bulk material, and how feedback between interior dynamics and surface-wide instabilities can further generate higher order buckling and wrinkling patterns. Building on these phenomena, we show how yet higher levels of feedback and spatiotemporal complexity can be programmed into hybrid materials, and how these mechanisms allow hybrid materials to be further integrated into multicompartmental systems capable of hierarchical chemo-mechano-chemical feedback responses. These responses no doubt represent only a small sample of the chemomechanical feedback behaviors waiting to be discovered in synthetic materials, and enable us to envision nearly limitless possibilities for designing multiresponsive, multifunctional, self-adapting materials and systems.

P. W. Wilson, W. Lu, H. Xu, P. Kim, M. J. Kreder, J. Alvarenga, J. Aizenberg, "Inhibition of Ice Nucleation by Slippery Liquid-Infused Porous Surfaces (SLIPS)," Physical Chem. Chem. Physics, 2013, 15, 581-585.

Ice repellent coatings have been studied and keenly sought after for many years, where any advances in the durability of such coatings will result in huge energy savings across many fields. Progress in creating anti-ice and anti-frost surfaces has been particularly rapid since the discovery and development of slippery, liquid infused porous surfaces (SLIPS). Here we use SLIPS-coated differential scanning calorimeter (DSC) pans to investigate the effects of the surface modification on the nucleation of supercooled water. This investigation is inherently different from previous studies which looked at the adhesion of ice to SLIPS surfaces, or the

formation of ice under high humidity conditions. Given the stochastic nature of nucleation of ice from supercooled water, multiple runs on the same sample are needed to determine if a given surface coating has a real and statistically significant effect on the nucleation temperature. We have cycled supercooling to freezing and then thawing of deionized water in hydrophilic (untreated aluminum), hydrophobic, superhydrophobic, and SLIPS-treated DSC pans multiple times to determine the effects of surface treatment on the nucleation and subsequent growth of ice. We find that SLIPS coatings lower the nucleation temperature of supercooled water in contact with statistical significance and show no deterioration or change in the coating performance even after 150 freeze–thaw cycles.

Awards

- Johns Hopkins University: The John C. & Florence W. Holtz Lectureship, September 2013
- R&D 100 Award for Top Technology and Innovation in 2013
- Hood Fellowship, University of Auckland, NZ, February 2013
- Fellow of the American Physical Society, March 2013
- David L. Weaver Endowed Lectureship in Biophysics and Computational Biology, UC Davis, April 2013

Presentations

- "Engineering and application of bioinspired structured materials," J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013.

- "Deposition of a transparent, omniphobic coating on arbitrarily shaped materials using layer-by-layer assembly" S. Sunny, N. Vogel, C. Howell, T. Vu, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013. [poster]

- "Colloidal monolayers for everyone: a simple approach to generate two-dimensional colloidal crystals over large areas on arbitrary substrates," N. Vogel, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013.

- "Bio-inspired structured materials showing omniphobicity at high temperatures" D. Daniel, M. N. Mankin, R. A. Belisle, T.-S. Wong, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013.

- "Stability of lubricant/liquid interfaces under flow," C. Howell, T. L. Vu, C. P. Johnson, X. Hou, N. Juthani, D. Fernandes, A. Carlson, L. Mahadevan, J. Alvarenga, O. Ahanotu, O. Uzun, P. Kim, J. Aizenberg. MRS Fall Meeting, Boston, MA, December 2013. [poster]

- "Topographically responsive ferrofluid-infused porous surfaces," W. D. Wang, T.-S. Wong, B. Hatton, S. H. Kang, J. Chi, R. T. Blough, S. Kennedy, D. Mooney, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013. [poster]

- “Bioinspired antifouling microfluidics," X. Hou, T. Wong, B. Hatton, Q. Liu, R. Belisle, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013.

- “Designing dynamic materials for controlled microscale mechanical stimulation of live cells," A. Sutton, L. Zarzar, T. Shirman, P. Kim, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013.

- “Tunable anisotropy in inverse opals: formation mechanism and effect on properties,” K. R. Phillips, N. Vogel, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013. [poster]

- “Interactive rational design of complex microstructures using microfluidics,” W. L. Noorduin, R. Sadza, L. Hendriks, S. K. Y. Tang, J. Aizenberg, MRS Fall meeting, Boston, MA, December 2013. (oral)

- “Fluorogel elastomer with superior omniphobicity, transparency and anti-biofouling properties," X. Yao, S. Dunn, P. Kim, M. Duffy, J. Alvarenga, J. Aizenberg, MRS Fall Meeting, Boston, MA, December 2013. (oral)

- “Utilizing chemo-mechanically functionalized oscillating fins to ‘catch and release’ nanoparticles in binary flow," Y. Liu, Y. Ma, A. Bhattacharya, O. Kuksenok, X. He, J. Aizenberg, A. Balazs, American Physical Society Division of Fluid Dynamics Annual Meeting, Pittsburgh, PA, November 24-26, 2013.

- “Self-organization of polymer nanofiber arrays for bioinspired multifunctional systems," S. H. Kang, J. Aizenberg, ASME International Mechanical Engineering Congress & Exposition, San Diego, CA, November 15-21, 2013. (oral and poster presentation)

- “Rationally designed complex, hierarchical micro-structures,” W. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, Mechanical Engineering seminar, Pennsylvania State University, University Park, PA, October 29, 2013. (oral)

- “Hydrogel-Actuated Integrated Responsive Systems (HAIRS): Moving Towards Adaptive, Homeostatic Materials," J.Aizenberg, Discovery Chemistry Seminar Series, Dupont Central Research & Development, Wilmington, DE, October 9, 2013.

- “Slippery Liquid-Infused Porous Surfaces (SLIPS)," P. Kim, Xerox Research Centre of Canada, Mississauga, Ontario, Canada, September 2013.

- “Hydrogel-actuated integrated responsive systems (HAIRS): moving towards adaptive, homeostatic materials,” J. Aizenberg, Department of Chemistry, University of Virginia, October 11, 2013.

- “Rationally designed complex, hierarchical micro-architectures,” W. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, Quantum Nanoscience, Delft, The Netherlands, September 25, 2013. (oral)

- “Hydrogel-actuated integrated responsive systems (HAIRS): moving towards adaptive, homeostatic materials,” J. Aizenberg, The John C. and Florence W. Holtz Lecture, Department of Chemical and Biomolecular Engineering, Johns Hopkins University, September 19, 2013

- “Rationally designed complex, hierarchical micro-structures,” W. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, XXII International Materials Research Congress, Cancún, Mexico, August 11, 2013. (oral)

- “Biomolecule catch and release by aptamer-functionalized adaptively reconfigurable dynamic systems,” A. Shastri, X. He, L. McGregor, Y. Vasquez, O. Kuksenok, A. Balazs, J. Aizenberg, Gordon Research Seminar on Soft Matter Physics, New London, NH, August 17-18, 2013. (poster)

- “The role of flagella in non-specific adhesion of Escherichia coli to structured abiotic surfaces,” R. S. Friedlander, H. Vlamakis, P. Kim, M. Khan, R. Kolter, J. Aizenberg, Gordon Research Conference on Microbial Adhesion and Signal Transduction, Newport, RI, July 21-26, 2013. [poster]

- “WICK - wetting in-color kit using chemically encrypted inverse colloidal crystals,” J. Aizenberg, I. Burgess, Programmable Self-Assembly of Matter Conference, New York City, NY, June 30, 2013.

- “Rationally designed complex, hierarchical micro-architectures," W. L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, Programmable Self-Assembly of Matter Conference, New York City, NY, June 30, 2013. (poster)

- “Fabrication of three-dimensional photonic structures utilizing composite colloids," T. Shirman, N. Vogel, M. Kolle, J. Aizenberg, Programmable Self-Assembly of Matter Conference, New York City, NY, June 30, 2013. (poster)

- “Nucleation and growth of rationally designed complex micro-architectures," J. Aizenberg, W. Noorduin, 87th Colloid Surface and Science Symposium, University of California, Riverside, June 23-26, 2013. [Plenary talk]

- "Novel self-regulating homeostatic materials," M. Aizenberg, X. He, J. Aizenberg, Frontiers in Macromolecular and Supramolecular Science, Bucharest, Romania, June 7-14, 2013.

- "Supramolecular assembly of inorganic species: rational design of complex 3D microarchitectures," J. Aizenberg, W. Noorduin, Frontiers in Macromolecular and Supramolecular Science, Bucharest, Romania, June 7-14, 2013.

- “Rationally designed complex hierarchical microarchitectures," W. L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, 14th Dutch Soft Matter Meeting, Twente University, Enschede, Netherlands, June 2013.

- “Building hierarchical structures," J. Aizenberg, Kavli Nanoscience Nexus Conference, Rio Grande, PR, May 29-June 1, 2013.

- “Combinatorial optofluidic sensing using colourimetric sensor arrays," B. A. Nerger, A. S. Chan, I. B. Burgess, N. Koay, M. H. Kinney, K. P. Raymond, J. Aizenberg, 96th Canadian Chemistry Conference and Exhibition, paper #568, Quebec, QC, Canada, May 27, 2013.

- “Dynamic photo-tunable wetting in inverse opal structures for colorimetric sensing and tunable fluidics," T.A. Singleton, A. Goulet-Hanssens, C. J. Barrett, I. B. Burgess, J. Aizenberg, B. A. Nerger, N. Koay, A. S. Chan, 96th Canadian Chemistry Conference and Exhibition, paper #438, Quebec, QC, Canada, May 27, 2013.

- “Slippery when wet: recreating nature’s most slippery surfaces with synthetic materials,” P. Kim, T.-S. Wong, J. Aizenberg, Hysitron, Inc., Eden Prairie, MN, May 22, 2013.

- “Materials to prevent ice accumulation," J. Aizenberg, Water Symposium, Weizmann Institute, Rehovot, Israel, May 22, 2013.

- “Rationally designed complex hierarchical micro-architectures," W. L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, Physical Chemistry Student Seminar Series, Columbia University, New York, NY, May 2013.

- “Responsive, self-regulated systems: from molecules to devices," J. Aizenberg, Gordon Research Conference (GRC) on Self-Assembly & Supramolecular Chemistry, Les Diablerets, Switzerland, May 5-10, 2013.

- “Novel omniphobic materials," J. Aizenberg, Ecole Polytechnique Federale de Lausanne (EPFL), Advances in Materials Seminar speaker, Lausanne, Switzerland, May 6, 2013.

- “Designing dynamic materials for controlled microscale mechanical stimulation of live cells," A. Sutton, L. Zarzar, P. Kim, J. Aizenberg, BioE Expo, Harvard University, Cambridge, MA, May 1 2013. [poster]

- “Bacterial flagella explore micro-scale hummocks and hollows to increase adhesion," R. S. Friedlander, H. Vlamakis, P. Kim, M. Khan, R. Kolter, J. Aizenberg, BioE Expo, Harvard University, Cambridge, MA, May 1 2013. [Poster]

- “Slippery when wet: liquid-infused nanostructured omni-repellent coatings and biomedical applications” P. Kim, New England Bioscience Society 2013 Annual Meeting, Harvard Medical School, Boston, MA, April 27, 2013.

- “Novel biomimetic ‘spiny’ surfaces in medical applications," J. Aizenberg, 2013 David L. Weaver Endowed Lecture in Biophysics and Computational Biology, UC Davis Genome Center, Davis, CA, April 24-26, 2013.

- “Bacterial flagella explore micro-scale hummocks and hollows to increase adhesion," R. S. Friedlander, H. Vlamakis, P. Kim, M. Khan, R. Kolter, J. Aizenberg, HST Forum, Boston, MA, April 11 2013. [Poster]

- “Everything SLIPS: design of novel omniphobic materials," J. Aizenberg, Princeton University, Princeton, NJ, April 17, 2013.

- “Tuning the optical properties of inverse opals via anisotropy,” K. R. Phillips, N. Vogel, J. Aizenberg, American Chemical Society Spring Meeting, New Orleans, LA, April 10, 2013. [oral]

- “Crystallinity and internal structure of photonic balls prepared by colloidal crystallization in the confinement of an emulsion droplet,” N. Vogel, S. Utech, M. Kolle, D. Weitz, J. Aizebenberg, ACS Meeting, New Orleans, April 2013

- “Structural and optical analysis of the bio-mineralized photonic structuresin the shell of the blue-rayed limpet *Ansates Pellucida*," M. Kolle, L. Li, S. Kolle, J. Weaver, C. Ortiz, J. Aizenberg, MRS Spring Meeting, San Francisco, CA, April 2013.

- “Nanostructured materials: from cell differentiation to antimicrobial surfaces," J. Aizenberg, Shriners Hospitals for Children, Boston, MA, March 29, 2013.

- “Biomineralization and Biomimetics: Multifunctionality in Biological Materials," J. Aizenberg, American Physical Society (APS) March Meeting 2013, Baltimore, MD, March 19, 2013.

- “Reaction-diffusion controlled growth of complex structures," W. L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, APS March Meeting 2013, Baltimore, MD, March 2013.

- “Structural and optical analysis of the bio-mineralized photonic structure in the shell of the blue-rayed limpet *Ansates pellucida*," M. Kolle, L. Li, S. Kolle, J. Weaver, C. Ortiz, J. Aizenberg, APS March Meeting 2013, Baltimore, MD, March 2013.

- “Emergence of complex structures by reaction-diffusion," W. L. Noorduin, L. Mahadevan, J. Aizenberg, 3rd Conference on Multifunctional Hybrid and Nanomaterials, Sorrento, Italy, March 2013.

- “Hydrogel-actuated integrated responsive systems (HAIRS): moving towards adaptive, homeostatic materials," J. Aizenberg, MIT, Cambridge, MA, February 27, 2013. [Plenary speaker]

- “Rational design of omni-repellent liquid-infused nanostructured surfaces and their manufacturable coating methods on a wide range of materials," P. Kim, M. J. Kreder, J. Alvarenga, J. Aizenberg, Smart Coatings 2013, Orlando, FL, February 20, 2013.

- “Squishy solutions to hard problems: traditional nanophotonics takes lessons from nature," I. B. Burgess, Chemical Engineering/Bioengineering seminar, McGill University, February 2013.

- "Wetting in color: from photonic fingerprinting of liquids to optical control of liquid percolation," I. B. Burgess, B. A. Nerger, K. P. Raymond, A. Goulet-Hanssens, T. A. Singleton, M. H. Kinney, C. J. Barrett, M. Loncar, J. Aizenberg, SPIE Photonics West, paper 8632-1, San Francisco, CA, February 2013. (Also serving as a chair for the Novel Phenomena and Devices in Photonic Crystals II session)

- “Biological photonic structures and their bio-inspired stimuli-responsive adaptive optical counterparts," M. Kolle, J. Aizenberg, SPIE Photonics West, San Francisco, CA, February 2013.

- ‘Homeostatic materials," M. Aizenberg, X. He, J. Aizenberg, Advanced Materials and Nanotechnology (AMN)-6 Conference, Auckland, New Zealand, February 11-February 15, 2013. [Keynote speaker]

- ‘Everything SLIPS: design of novel omniphobic materials," J. Aizenberg, Advanced Materials and Nanotechnology (AMN)-6 Conference, Auckland, New Zealand, February 11-February 15, 2013. [Keynote speaker]

- “Cells in and on nano/micro forests," J. Aizenberg, NanoEngineering for Medicine & Biology (NEMB) 2013 Conference, Boston, MA, February 6, 2013.

KIBST-related activities

Co-Organized the Kavli Nano-Nexus Conference at the Gran Melia Resort, Puerto Rico.

Group members participated in weekly Kavli Koffee talks on Structural Color.

George M. Whitesides

Co-Director of The Kavli Institute at Harvard University

Professor of Chemistry

Department of Chemistry and Chemical Biology

Professor Whitesides and his group work in four areas: biochemistry, materials science, catalysis and physical organic chemistry. Each of these areas requires development of the fundamental skills of experimental chemistry - synthesis and characterization of new compounds, examination of relations between molecular structure and reactivity or physical properties - but each, in addition, develops skill in other techniques - surface spectroscopy, microbiology, electron microscopy, ellipsometry, reactor design, measurement of such physical properties. The group is eclectic and generalist in its approach: at different times research on a particular problem may require organic synthesis, organometallic chemistry, spectroscopy, computer analysis, biochemistry, molecular biology or a wide range of other techniques.

The specific foci of the research vary widely. Work in biochemistry currently centers on adhesion of mammalian cells, viruses and bacteria to surfaces, polyvalency, rational drug design, and biophysical studies centered around capillary electrophoresis and surface plasmon resonance spectroscopy. Those coworkers concerned with materials science are occupied with the fabrication of nanostructures, microfluidic systems, microelectromechanical systems, and 3-D microstructures. The synthesis and characterization of structurally well-defined organic surfaces (especially using self-assembled monolayers) and solids, and the use of these assemblies to study physical properties such as wettability and biocompatibility, are an important component of this work. This area also includes studies in physical optics and unconventional methods of lithography (soft lithography; various forms of near-field optical lithography). Much of the work in catalysis centers on fuel cells. Problems in physical-organic chemistry address issues in self-assembly, especially using meso-scale systems (objects with dimensions from 10 μm - 10 mm, held together by capillary and/or magnetic forces). Computation and simulation is also important tools in the group.

The group uses classical chemical techniques to work in areas of research that lie at the boundaries between chemistry and biology, catalysis, solid state physics, and engineering. Students who work in the group emerge as generalists, and there is a strong emphasis in learning how to carry out multidisciplinary and multiinvestigator research, and how to communicate the results of research effectively.

List of papers acknowledging the Kavli Foundation with abstracts appended

R. V., Branch, J. L., Fish, C. R., Lin, L., Suo, Z. and Whitesides, G. M., "Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers ", Martinez, Advanced Materials, 2013, 25, 205-212.

> This communication describes the design and fabrication of soft tentacles based on micropneumatic networks spatially distributed at the interface of two different elastomers; these composite elastomeric structures enable complex 3D motion of the tentacles. We demonstrate both the range of motion open to these tentacles, and their capability to grip and manipulate objects with complex shapes. We also extend the capabilities of these soft actuators by embedding functional components (for example, a needle for delivering fluid, a video camera, and a suction cup) in them. We further demonstrate that modifying the texture of the surface of the tentacles can improve their adhesion to slippery surfaces.

Keplinger, C., Sun, J.-Y., Foo, C., Whitesides, G. M. and Suo, Z. G., "Stretchable, Transparent, Ionic Conductors", Science, 2013, 341, 984-987.

> Existing stretchable, transparent conductors are mostly electronic conductors. They limit the performance of interconnects, sensors, and actuators as components of stretchable electronics and soft machines. We describe a class of devices enabled by ionic conductors that are highly stretchable, fully transparent to light of all colors, and capable of operation at frequencies beyond 10 kilohertz and voltages above 10 kilovolts. We demonstrate a transparent actuator that can generate large strains and a transparent loudspeaker that produces sound over the entire audible range. The electromechanical transduction is achieved without electrochemical reaction. The ionic conductors have higher resistivity than many electronic conductors; however, when large stretchability and high transmittance are required, the ionic conductors have lower sheet resistance than all existing electronic conductors.

Bwambok, D. K., Thuo, M. M., Atkinson, M. B. J., Mirica, K. A., Shapiro, N. D. and Whitesides, G. M., "Paramagnetic Ionic Liquids for Measurements of Density Using Magnetic Levitation", Analytical Chemistry, 2013, 85, 8442-8447.

> Paramagnetic ionic liquids (PILs) provide new capabilities to measurements of density using magnetic levitation (MagLev). In a typical measurement, a diamagnetic object of unknown density is placed in a container containing a PIL. The container is placed between two magnets (typically NdFeB, oriented with like poles facing). The density of the diamagnetic object can be determined by measuring its position in the magnetic field along the vertical axis (levitation

height, h), either as an absolute value or relative to internal standards of known density. For density measurements by MagLev, PILs have three advantages over solutions of paramagnetic salts in aqueous or organic solutions: (i) negligible vapor pressures; (ii) low melting points; (iii) high thermal stabilities. In addition, the densities, magnetic susceptibilities, glass transition temperatures, thermal decomposition temperatures, viscosities, and hydrophobicities of PILs can be tuned over broad ranges by choosing the cation–anion pair. The low melting points and high thermal stabilities of PILs provide large liquidus windows for density measurements. This paper demonstrates applications and advantages of PILs in density-based analyses using MagLev.

Drews, A. M., Cademartiri, L., Whitesides, G. M. and Bishop, K. J. M. J., "Electric Winds Driven by Time Oscillating Corona Discharges", Appl. Phys., 2013, 114, 143302.

We investigate the formation of steady gas flows—so-called electric winds—created by point-plane corona discharges driven by time oscillating (ac) electric fields. By varying the magnitude and frequency of the applied field, we identify two distinct scaling regimes: (i) a low frequency (dc) regime and (ii) a high frequency (ac) regime. These experimental observations are reproduced and explained by a theoretical model describing the transport and recombination of ions surrounding the discharge and their contribution to the measured wind velocity. The two regimes differ in the spatial distribution of ions and in the process by which ions are consumed. Interestingly, we find that ac corona discharges generate strong electric forces localized near the tip of the point electrode, while dc corona discharges generate weaker forces distributed throughout the interelectrode region. Consequently, the velocity of the electric winds (>1 m/s) generated by ac discharges is largely independent of the position of the counter electrode. The unified theoretical description of dc and ac electric winds presented here reconciles previous observations of winds driven by dc corona and ac dielectric barrier discharges; insights from the model should also prove useful in the design of other plasma actuators.

Soh, S., Chen, X., Vella, S. J., Choi, W., Gong, J. and Whitesides, G. M., "Layer-by-Layer Films for Tunable and Rewritable Control of Contact Electrification", Soft Matter, 2013, 9, 10233-10238.

Charges generated by contact of solid surfaces (contact electrification) can be hazardous or useful depending on the circumstance. This paper describes a process to design a solid surface rationally to either induce or prevent charging during contact electrification; this process coats the surface with polyelectrolytes. It is observed experimentally that a surface coated with a layer of a polymer having multiple, covalently attached positive charges (a “polycation”) develops a positive charge after contacting another surface; a surface coated with a layer of polymer having negative charges (a “polyanion”) develops a negative charge. By coating the surface using layer-bylayer (LBL) deposition, the tendency of the surface to charge either positively or negatively can be switched: adding a layer of polyelectrolyte with charge opposite to the charge on the surface switches the polarity of the surface. Through microcontact printing (mCP), the surface can be stamped to create a mosaic pattern of polycation and polyanion—and importantly, the fraction of the surface area covered with polycation and polyanion can be tuned by using stamps of different patterns. Using poly(diallyldimethylammonium chloride) (PDDA) as the polycation and poly(sodium 4-styrenesulfonate) (PSS) as the polyanion, it is found that for a surface with >75% PSS, the

surface charges negatively; with <75% PSS, the surface charges positively. At 75% PSS, the surface becomes non-charging. The patterns on the surface can, subsequently, be erased through coating the surface with a uniform layer of polyelectrolyte. After erasing, the surface is rewritable by depositing or patterning the surface with a desired polyelectrolyte.

Drews, A. M., Cademartiri, L., Whitesides, G. M. and Bishop, K. J. M. J., "Electric Winds Driven by Time Oscillating Corona Discharges", Appl. Phys., 2013, 114, 143302.

We investigate the formation of steady gas flows—so-called electric winds—created by point-plane corona discharges driven by time oscillating (ac) electric fields. By varying the magnitude and frequency of the applied field, we identify two distinct scaling regimes: (i) a low frequency (dc) regime and (ii) a high frequency (ac) regime. These experimental observations are reproduced and explained by a theoretical model describing the transport and recombination of ions surrounding the discharge and their contribution to the measured wind velocity. The two regimes differ in the spatial distribution of ions and in the process by which ions are consumed. Interestingly, we find that ac corona discharges generate strong electric forces localized near the tip of the point electrode, while dc corona discharges generate weaker forces distributed throughout the interelectrode region. Consequently, the velocity of the electric winds (>1 m/s) generated by ac discharges is largely independent of the position of the counter electrode. The unified theoretical description of dc and ac electric winds presented here reconciles previous observations of winds driven by dc corona and ac dielectric barrier discharges; insights from the model should also prove useful in the design of other plasma actuators.

Soh, S., Chen, X., Vella, S. J., Choi, W., Gong, J. and Whitesides, G. M. , "Layer-by-Layer Films for Tunable and Rewritable Control of Contact Electrification", Soft Matter, 2013, 9, 10233-10238.

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Awards

- Gold Medal (Industrial Research Institute) (2013)

Honorary Degrees

- State University of New York, Birmingham (2013)
- University of Victoria, British Columbia (Canada, 2013)

KIBST-related activities

Participated in the Kavli Nano-Nexus Conference at the Gran Melia Resort, Puerto Rico.

Michael P. Brenner

Glover Professor of Applied Mathematics and Applied Physics

Harvard College Professor

School of Engineering and Applied Sciences

Michael Brenner's research uses methods and ideas of applied mathematics to address problems in science and engineering. We are first and foremost problem solvers, and search widely to find problems where mathematics (simple or complicated, with large computer simulations or without) can answer scientific questions.

Over the past decade our research has focused essentially primarily on theoretical modeling in the physical sciences and engineering. Much of the work has arisen out of close contact with experimentalists, and efforts to develop quantitative descriptions of phenomena and experiments. Problems addressed have included the breaking of fluid droplets; sonoluminescence (the production of light from small bubbles); the sedimentation of small particles; device design in engineering; electrospinning (a materials technique for producing small fibers), etc.

Current projects in the physical sciences include problems in microfluidics (such as mechanisms for producing small fibers in microfluidic devices), fluid mechanics (such as the aerodynamics of whale flippers), the rheology of colloidal suspensions (such the mechanisms underlying shear banding), self assembly, as well as various problems in material science (ion beam sputtering), and atmospheric chemistry (algorithm development for speeding up current atmospheric transport codes, as well as fundamental research into nonlinear chemical plumes in the atmosphere).

In recent years more and more of our work has been moving to biological questions and biological phenomena. We are interested in this both because the problems themselves are of interest and have much opportunity, and also because we feel strongly that the principles of biology can be used to develop novel directions in engineering. Current projects range from the connection between evolution and physiology (primarily in voltage gated ion channels, and hemoglobin), to the mechanism of transport in the nuclear pore, to issues having to do with understanding the very large systems of differential equations that commonly arise in biological modeling.

List of papers acknowledging the Kavli Foundation with abstracts appended

S.Hormoz and M.P. Brenner, Non universal and non singular asymptotics of interacting vortex filaments, Proc. IUTAM, 7, 97-106 (2013).

We present a method for calculating the asymptotic shape of interacting vortex filaments in incompressible Euler flows using delay differential equations. Neglecting the filaments' core-size, the asymptotic shape of the filaments is self-similar up to logarithmic corrections, albeit non-universal. We demonstrate explicitly that the asymptotic geometry of the collapse of two interacting fil- aments depends on the pre-factor of the scaling law of their separation distance, the angle between the tangent vectors at their approaching tips, and the ratio of their circulations. We then explore the validity of the filament approximation in the limit of approaching the singularity. We show that a sufficiently fast stretching-rate to maintain this approximation is inconsistent with all collapse geometries. This suggests that a singular solution to the Euler equations based on stretching of vortex filaments is unlikely to exist for any initial conditions.

J.Fritz, A. Seminara, M. Roper, A. Pringle and M.P. Brenner, A natural O-ring optimizes the dispersal of fungal spores, Journ. R. Soc. Interface, 6,20130187 (2013).

The forcibly ejected spores of ascomycete fungi must penetrate several millimetres of nearly still air surrounding sporocarps to reach dispersive airflows, and escape is facilitated when a spore is launched with large velocity. To launch, the spores of thousands of species are ejected through an apical ring, a small elastic pore. The startling diversity of apical ring and spore shapes and dimensions make them favoured characters for both species descriptions and the subsequent inference of relationships among species. However, the physical constraints shaping this diversity and the adaptive benefits of specific morphologies are not understood. Here, we develop an elastohydrodynamic theory of the spore's ejection through the apical ring and demonstrate that to avoid enormous energy losses during spore ejection, the four principal morphological dimensions of spore and apical ring must cluster within a nonlinear one-dimensional subspace. We test this prediction using morphological data for 45 fungal species from two different classes and 18 families. Our sampling encompasses multiple loss and gain events and potentially independent origins of this spore ejection mechanism. Although the individual dimensions of the spore and apical ring are only weakly correlated with each other, they collapse into the predicted subspace with high accuracy. The launch velocity appears to be within 2 per cent of the optimum for over 90 per cent of all forcibly ejected species. Although the morphological diversity of apical rings and spores appears startlingly diverse, a simple principle can be used to organize it.

M.Holmes-Cerfon, S. Gortler and M.P. Brenner, A Geometrical Approach to computing free energy landscapes from short ranged potentials, Proc. Natl. Acad. Sci, 110, E5-E14, (2013).

Particles interacting with short-ranged potentials have attracted increasing interest, partly for their ability to model mesoscale systems such as colloids interacting via DNA or depletion. We consider the free-energy landscape of such systems as the range of the potential goes to zero. In this limit, the landscape is entirely defined by geometrical manifolds, plus a single control

parameter. These manifolds are fundamental objects that do not depend on the details of the interaction potential and provide the starting point from which any quantity characterizing the system—equilibrium or nonequilibrium—can be computed for arbitrary potentials. To consider dynamical quantities we compute the asymptotic limit of the Fokker–Planck equation and show that it becomes restricted to the low-dimensional manifolds connected by "sticky" boundary conditions. To illustrate our theory, we compute the low-dimensional manifolds for $n \leq 8$ identical particles, providing a complete description of the lowest-energy parts of the landscape including floppy modes with up to 2 internal degrees of freedom. The results can be directly tested on colloidal clusters. This limit is a unique approach for understanding energy landscapes, and our hope is that it can also provide insight into finite-range potentials.

J.Wilking, V. Zaburdaev, M.De Volder, R. Losick, M.P. Brenner and D.A. Weitz, Liquid transport facilitated by channels in Bacillus subtilus biofilms, Proc. Natl. Acad. Sci, 110, 848-852 (2013).

Many bacteria on earth exist in surface-attached communities known as biofilms. These films are responsible for manifold problems, including hospital-acquired infections and biofouling, but they can also be beneficial. Biofilm growth depends on the transport of nutrients and waste, for which diffusion is thought to be the main source of transport. However, diffusion is ineffective for transport over large distances and thus should limit growth. Nevertheless, biofilms can grow to be very large. Here we report the presence of a remarkable network of well-defined channels that form in wild-type *Bacillus subtilis* biofilms and provide a system for enhanced transport. We observe that these channels have high permeability to liquid flow and facilitate the transport of liquid through the biofilm. In addition, we find that spatial variations in evaporative flux from the surface of these biofilms provide a driving force for the flow of liquid in the channels. These channels offer a remarkably simple system for liquid transport, and their discovery provides insight into the physiology and growth of biofilms.

K. Alim, G. Amselem, F. Peaudecerf, M.P. Brenner and A. Pringle, Organism wide organization of flow by random network peristalsis in *Physarum polycephalum*, Proc. Natl. Acad. Sci, 110,13306 (2013).

Individuals can function as integrated organisms only when information and resources are shared across a body. Signals and substrates are commonly moved using fluids, often channeled through a network of tubes. Peristalsis is one mechanism for fluid transport and is caused by a wave of cross-sectional contractions along a tube. We extend the concept of peristalsis from the canonical case of one tube to a random network. Transport is maximized within the network when the wavelength of the peristaltic wave is of the order of the size of the network. The slime mold *Physarum polycephalum* grows as a random network of tubes, and our experiments confirm peristalsis is used by the slime mold to drive internal cytoplasmic flows. Comparisons of theoretically generated contraction patterns with the patterns exhibited by individuals of *P. polycephalum* demonstrate that individuals maximize internal flows by adapting patterns of contraction to size, thus optimizing transport throughout an organism. This control of fluid flow may be the key to coordinating growth and behavior, including the dynamic changes in network architecture seen over time in an individual.

Awards

- Stanley Corrsin Award, American Physical Society (2013)
- *For his intellectual leadership in fluid dynamics and in particular for his seminal contributions to electrohydrodynamics and droplet splashing*
- Elected Fellow, American Academy of Arts and Sciences, 2014

Presentations

- Geilo Winter School, Norway, keynote lecture
- Gordon Research Seminar on Self-Assembly and Supramolecular Chemistry, Switzerland
- SIAM Meeting on Materials Science, Plenary Lecture
- George Washington University, Food Science Lecture
- Princeton Applied and Computational Mathematics Distinguished Lecture
- Brandeis University Physics Colloquium
- Distinguished speaker Seminar, Department of Materials Science, Northwestern
- Evolution of Colloidal Matter, New York University
- Programmable Self-Assembly of Matter, New York University
- Kavli Nexus in Bio-nano Science, Puerto Rico
- Gordon Conference on Soft Condensed Matter Physics, New Hampshire
- Simons Foundation Lecture Series, NYC
- Mathematics Colloquium, Courant Institute
- Stanley Corrsin Lecture, Division of Fluid Dynamics Annual Meeting
- Von Neumann Symposium, Rockefeller University
- Imagery for Material Structure, University of Chicago

KIBST-related activities

Launched edX class on *Science and Cooking*. > 94,000 people enrolled.

https://www.edx.org/course/harvardx/harvardx-spu27x-science-cooking-haute-639#.U077BeZdXZo

Hosted weekly Kavli Koffee Hour at SEAS – an hour of sharing research from interdisciplinary fields.

L. Mahadevan

Lola England de Valpine Professor of Applied Mathematics,

Professor of Organismic and Evolutionary Biology,

Professor of Physics

School of Engineering and Applied Sciences

Our work in the area of Bionano Science and Technology has focused on a number of problems that span a range of scales from the molecular to the macroscopic. The Kavli Institute has been central to us in allowing us to explore problems that we would never have had an opportunity to explore otherwise, since they are off the beaten track.

These include problems in plant and animal morphogenesis, macro-molecular structure and dynamics, pattern formation at the nanoscale, and associated problems in applied mathematics and soft matter physics that these applications naturally led to. These have led to a number of papers with collaborations across many different fields, mathematics, physics, biology, engineering, medicine etc.

In addition to the papers that we have published in the last two years that are supported by the Kavli Institute, we have recently begun work on some problems that probe the boundary between physics and cognitive science, both areas of interest at other Kavli Institutes. In this spirit, I am a co-director of the newly established Summer School on Brains, Minds and Machines at MBL, Woods Hole, MA.

List of papers acknowledging the Kavli Foundation with abstracts appended

J. M. Kolinski, S. M. Rubinstein, S. Mandre, M. P. Brenner, D. A. Weitz, and L. Mahadevan, "Skating on a film of air: drops impacting on a surface", Physical Review Letters, 108, 074503, (2012).

> The commonly accepted description of drops impacting on a surface typically ignores the essential role of the air that is trapped between the impacting drop and the surface. Here we describe a new imaging modality that is sensitive to the behavior right at the surface. We show that a very thin film of air, only a few tens of nanometers thick, remains trapped between the falling drop and the surface as the drop spreads. The thin film of air serves to lubricate the drop enabling the fluid to skate on the air film laterally outward at surprisingly high velocities, consistent with theoretical predictions. Eventually this thin film of air breaks down as the fluid wets the surface via a spinodal-like mechanism. Our results show that the dynamics of impacting drops are much more complex than previously thought, with a rich array of unexpected phenomena that require rethinking classic paradigms.

V.R. Tirumala, C.M. Stafford, L.E. Ocola, J.F. Douglas, and L. Mahadevan, "Geometric control of rippling in supported polymer nanolines Nanoletters, " 12, 1516-1521, (2012).

We study the swelling behavior of finlike polymer line gratings supported on a rigid substrate and show that the edge-supported polymer laminae undergo a rippling instability with a well-defined ripple wavelength λ transverse to the plane of the solid supporting substrate and a ripple amplitude that monotonically decreases from its maximum at the free-edge. These ripple patterns develop due to inhomogeneous compressive strains that arise from the geometric constraints that progressively suppress swelling near the supporting substrate where the laminae are clamped. By experimentally examining the influence of swelling strain and pattern geometry on the observed rippling instability, we find that the ripple wavelength λ scales with line width w for sufficiently long gratings, which is consistent with a simple theory. These trends were validated for polymer nanoline test patterns having w between (50 to 250) nm and a height-to-width aspect-ratio in the range 0.5 to 5. Our results suggest that line geometry, rather than material properties, governs the onset of rippling and suggest simple rules for their control.

L. Giomi, L Mahadevan, B. Chakraborty and M. F. Hagan,"Banding, excitability and chaos in active nematic suspensions" Nonlinearity 25, 2245–2269 (2012).

Motivated by the observation of highly unstable flowing states in suspensions of microtubules and kinesin, we analyse a model of mutually propelled filaments suspended in a solvent. The system undergoes a mean-field isotropic–nematic transition for large enough filament concentrations when the nematic order parameter is allowed to vary in space and time. We analyse the model in two contexts: a quasi-one-dimensional channel with no-slip walls and a two-dimensional box with periodic boundaries. Using stability analysis and numerical calculations we show that the interplay between non-uniform nematic order, activity, and flow results in a variety of complex scenarios that include spontaneous banded laminar flow, relaxation oscillations and chaos.

O. Sahin, E-H Yong, A. Driks and L. Mahadevan, "Physical basis for the adaptive flexibility of bacillus spore coats", Journal of the Royal Society - Interface, 9, 3156-3160 (2012).

Bacillus spores are highly resistant dormant cells formed in response to starvation. The spore is surrounded by a structurally complex protein shell, the coat, which protects the genetic material. In spite of its dormancy, once nutrient is available (or an appropriate physical stimulus is provided) the spore is able to resume metabolic activity and return to vegetative growth, a process requiring the coat to be shed. Spores dynamically expand and contract in response to humidity, demanding that the coat be flexible. Despite the coat's critical biological functions, essentially nothing is known about the design principles that allow the coat to be tough but also flexible and, when metabolic activity resumes, to be efficiently shed. Here, we investigated the hypothesis that these apparently incompatible characteristics derive from an adaptive mechanical response of the coat. We generated a mechanical model predicting the emergence and dynamics of the folding patterns uniformly seen in Bacillus spore coats. According to this model, spores carefully harness mechanical instabilities to fold into a wrinkled pattern during sporulation. Owing to the inherent nonlinearity in their formation, these wrinkles persist during dormancy and allow the spore to accommodate changes in volume without compromising structural and biochemical integrity. This characteristic of the spore and its coat may inspire design of adaptive materials.

P. Mellado, A. Concha, L. Mahadevan, “Macroscopic magnetic frustration”, Physical Review Letters, 109, 257203 (2012).

Although geometrical frustration transcends scale, it has primarily been evoked in the micro- and mesoscopic realm to characterize such phases as spin ice, liquids, and glasses and to explain the behavior of such materials as multiferroics, high-temperature superconductors, colloids, and copolymers. Here we introduce a system of macroscopic ferromagnetic rotors arranged in a planar lattice capable of out-of-plane movement that exhibit the characteristic honeycomb spin ice rules studied and seen so far only in its mesoscopic manifestation. We find that a polarized initial state of this system settles into the honeycomb spin ice phase with relaxation on multiple time scales. We explain this relaxation process using a minimal classical mechanical model that includes Coulombic interactions between magnetic charges located at the ends of the magnets and viscous dissipation at the hinges. Our study shows how macroscopic frustration arises in a purely classical setting that is amenable to experiment, easy manipulation, theory, and computation, and shows phenomena that are not visible in their microscopic counterparts.

F.Y. Lim, K.-H. Chaim, and L. Mahadevan, “The size, shape, and dynamics of cellular blebs”, Europhysics Letters, 100, 28004 (2012).

A cellular bleb grows when a portion of the cell membrane detaches from the underlying cortex under the influence of a cytoplasmic pressure. We develop a quantitative model for the growth and dynamics of these objects in a simple two-dimensional setting. In particular, we first find the minimum cytoplasmic pressure and minimum unsupported membrane length for a stationary bleb to nucleate and grow as a function of the membrane-cortex adhesion. We next show how a bleb may travel around the periphery of the cell when the cytoplasmic pressure varies in space and time in a prescribed way and find that the traveling speed is governed by the speed of the pressure change induced by local cortical contraction while the shape of the traveling blebs governed by the speed of cortical healing. Finally, we relax the assumption that the pressure change is prescribed and couple it hydrodynamically to the cortical contraction and membrane deformation. By quantifying the phase space of bleb formation and dynamics, our framework serves to delineate the range and scope of bleb-associated cell motility.

L. Giomi, N. Hawley-Weld and L. Mahadevan, “Swarming, swirling and stasis in sequestered bristle-bots”, Proceedings of the Royal Society (A), 469, 20120637.

The collective ability of organisms to move coherently in space and time is ubiquitous in any group of autonomous agents that can move and sense each other and the environment. Here, we investigate the origin of collective motion and its loss using macroscopic self-propelled bristle-bots, simple automata made from a toothbrush and powered by an onboard cell phone vibrator-motor, that can sense each other through shape-dependent local interactions, and can also sense the environment non-locally via the effects of confinement and substrate topography. We show that when bristle-bots are confined to a limited arena with a soft boundary, increasing the density drives a transition from a disordered and uncoordinated motion to organized collective motion either as a swirling cluster or a collective dynamical stasis. This transition is regulated by a single parameter, the relative magnitude of spinning

and walking in a single automaton. We explain this using quantitative experiments and simulations that emphasize the role of the agent shape, environment and confinement via boundaries.

Our study shows how the behavioural repertoire of these physically interacting automatons controlled by one parameter translates into the mechanical intelligence of swarms.

E. Moeendarbary, L. Valon, M. Fritzsche, A.R. Harris, D.A. Moulding, A.J. Thrasher, E. Stride, L. Mahadevan, and G.T. Charras, "The cytoplasm of living cells behaves as a poroelastic material" Nature Materials, 12, 253-261 (2013).

The cytoplasm is the largest part of the cell by volume and hence its rheology sets the rate at which cellular shape changes can occur. Recent experimental evidence suggests that cytoplasmic rheology can be described by a poroelastic model, in which the cytoplasm is treated as a biphasic material consisting of a porous elastic solid meshwork (cytoskeleton, organelles, macromolecules) bathed in an interstitial fluid (cytosol). In this picture, the rate of cellular deformation is limited by the rate at which intracellular water can redistribute within the cytoplasm. However, direct supporting evidence for the model is lacking.

Here we directly validate the poroelastic model to explain cellular rheology at short timescales using microindentation tests in conjunction with mechanical, chemical and genetic treatments. Our results show that water redistribution through the solid phase of the cytoplasm (cytoskeleton and macromolecular crowders) plays a fundamental role in setting cellular rheology at short timescales.

T. Tallinen, J.S. Biggins, and L. Mahadevan, "Surface sulci in squeezed soft solids", Physical Review Letters, 110, 024302, (2013).

The squeezing of soft solids, the constrained growth of biological tissues, and the swelling of soft elastic solids such as gels can generate large compressive stresses at their surfaces. This causes the otherwise smooth surface of such a solid to become unstable when its stress exceeds a critical value.

Previous analyses of the surface instability have assumed two-dimensional plane-strain conditions, but in experiments isotropic stresses often lead to complex three-dimensional sulcification patterns. Here we show how such diverse morphologies arise by numerically modeling the lateral compression of a rigidly clamped elastic layer. For incompressible solids, close to the instability threshold, sulci appear as **I**-shaped lines aligned orthogonally with their neighbors; at higher compressions they are **Y**-shaped and prefer a hexagonal arrangement. In contrast, highly compressible solids when squeezed show only one sulcified phase characterized by a hexagonal sulcus network.

L. Giomi, N. Hawley-Weld and L. Mahadevan, "Swarming, swirling and stasis in sequestered bristle-bots", Proceedings of the Royal Society (A), 469, 20120637.

The collective ability of organisms to move coherently in space and time is ubiquitous in any group of autonomous agents that can move and sense each other and the environment. Here, we investigate the origin of collective motion and its loss using macroscopic self-propelled bristle-bots, simple automata made from a toothbrush and powered by an onboard cell phone vibrator-motor, that can sense each other through shape-dependent local interactions, and can also sense the environment nonlocally via the effects of confinement and substrate topography. We show that when bristle-bots are confined to a limited arena with a soft boundary, increasing the density drives a transition from a disordered and uncoordinated motion to organized collective motion either as a swirling cluster or a collective dynamical stasis. This transition is regulated by a single parameter, the relative magnitude of spinning and walking in a single automaton. We explain this using quantitative experiments and simulations that emphasize the role of the agent shape, environment and confinement via boundaries.

Our study shows how the behavioural repertoire of these physically interacting automatons controlled by one parameter translates into the mechanical intelligence of swarms.

A.C. Slim, M.M. Bandi, J.C. Miller, and L. Mahadevan, "Dissolution-driven convection in a Hele-Shaw cell", Physics of Fluids, 25, 024101 (2013).

Motivated by convection in the context of geological carbon-dioxide (CO_2) storage, we present an experimental study of dissolution-driven convection in a Hele–Shaw cell for Rayleigh numbers R in the range $100 < R < 1700$. We use potassium permanganate ($KMnO_4$) in water as an analog for CO_2 in brine and infer concentration profiles at high spatial and temporal resolution and accuracy from transmitted light intensity. We describe behavior from first contact up to 65% average saturation and measure several global quantities including dissolution flux, average concentration, amplitude of perturbations away from pure one-dimensional diffusion, and horizontally averaged concentration profiles. We show that the flow evolves successively through distinct regimes starting with a simple one-dimensional diffusional profile.

This is followed by linear growth in which fingers are initiated and grow quasiexponentially, independently of one-another. Once the fingers are well-established, a flux-growth regime begins as fresh fluid is brought to the interface and contaminated fluid removed, with the flux growing to a local maximum. During this regime, fingers still propagate independently. However, beyond the flux maximum, fingers begin to interact and zip together from the root down in a merging regime. Several generations of merging occur before only persistent primary fingers remain. Beyond this, the reinitiation regime begins with new fingers created between primary existing ones before merging into them. Through appropriate scaling, we show that the regimes are universal and independent of layer thickness (equivalently R) until the fingers hit the bottom. At this time, progression through these regimes is interrupted and the flow transitions to a saturating regime. In this final regime, the flux gradually decays in a manner well described by a Howard-style phenomenological model.

G.W. Jones and L. Mahadevan, "Planar morphometry, shear and optimal quasi-conformal mappings", Proceedings of the Royal Society (A), 469, 20120653 (2013).

To characterize the diversity of planar shapes in such instances as insect wings and plant leaves, we present a method for the generation of a smooth morphometric mapping between two planar domains which matches a number of homologous points. Our approach tries to balance the competing requirements of a descriptive theory which may not reflect mechanism and a multi-parameter predictive theory that may not be well constrained by experimental data. Specifically, we focus on aspects of shape as characterized by local rotation and shear, quantified using quasi-conformal maps that are defined precisely in terms of these fields. To make our choice optimal, we impose the condition that the maps vary as slowly as possible across the domain, minimizing their integrated squared-gradient. We implement this algorithm numerically using a variational principle that optimizes the coefficients of the quasi-conformal map between the two regions and show results for the recreation of a sample historical grid deformation mapping of D'Arcy Thompson. We also deploy our method to compare a variety of Drosophila wing shapes and show that our approach allows us to recover aspects of phylogeny as marked by morphology.

S.I.A. Cohen and L. Mahadevan, "Hydrodynamics of hemostasis in sickle-cell disease", Physical Review Letters, 110, 138104 (2013).

Vaso-occlusion, the stoppage of blood flow in sickle-cell disease, is a complex dynamical process spanning multiple time and length scales. Motivated by recent ex vivo microfluidic measurements of hemostasis using blood from sickle-cell patients, we develop a multiphase model that couples the kinetics and hydrodynamics of a flowing suspension of normal and sickled cells in a fluid. We use the model to derive expressions for the cell velocities and concentrations that quantify the hydrodynamics of hemo-stasis, and provide simple criteria as well as a phase diagram for occlusion, consistent with our simulations and earlier observations.

X. Yao, Y. Hu, A. Grinthal, T-S. Wong, L. Mahadevan and J. Aizenberg, "Adaptive fluid-infused porous films with tunable transparency and wettability" Nature Materials, 12, 529-34 (2013).

Materials that adapt dynamically to environmental changes are currently limited to two-state switching of single properties, and only a small number of strategies that may lead to materials with continuously adjustable characteristics have been reported1–3. Here we introduce adaptive surfaces made of a liquid film supported by a nanoporous elastic substrate.

As the substrate deforms, the liquid flows within the pores, causing the smooth and defect-free surface to roughen through a continuous range of topographies. We show that a graded mechanical stimulus can be directly translated into finely tuned, dynamic adjustments of optical transparency and wettability. In particular, we demonstrate simultaneous control of the film's transparency and its ability to continuously manipulate various low-surface-tension droplets from freesliding to pinned. This strategy should make possible the rational design of tunable, multifunctional adaptive materials for a broad range of applications.

W.L. Noorduin, A. Grinthal, L. Mahadevan, J. Aizenberg, "Rationally designed complex, hierarchical microarchitectures", Science, 340, 832-837.

The emergence of complex nano- and microstructures is of fundamental interest, and the ability to program their form has practical ramifications in fields such as optics, catalysis, and electronics. We developed carbonate-silica microstructures in a dynamic reaction-diffusion system that allow us to rationally devise schemes for precisely sculpting a great variety of elementary shapes by diffusion of carbon dioxide (CO_2) in a solution of barium chloride and sodium metasilicate. We identify two distinct growth modes and show how continuous and discrete modulations in CO_2 concentration, pH, and temperature can be used to deterministically switch between different regimes and create a bouquet of hierarchically assembled multiscale microstructures with unprecedented levels of complexity and precision. These results outline a nanotechnology strategy for "collaborating" with self-assembly processes in real time to build arbitrary tectonic architectures.

Z.Y. Wei, Z.V. Guo, L. Dudte, H.Y. Liang, and L. Mahadevan, "Geometric mechanics of periodic pleated origami", Physical Review Letters, 110, 215501 (2013).

Origami structures are mechanical metamaterials with properties that arise almost exclusively from the geometry of the constituent folds and the constraint of piecewise isometric deformations. Here we characterize the geometry and planar and nonplanar effective elastic response of a simple periodically folded Miura-ori structure, which is composed of identical unit cells of mountain and valley folds with four-coordinated ridges, defined completely by two angles and two lengths. We show that the in-plane and out-of-plane Poisson's ratios are equal in magnitude, but opposite in sign, independent of material properties. Furthermore, we show that effective bending stiffness of the unit cell is singular, allowing us to characterize the two-dimensional deformation of a plate in terms of a one-dimensional theory. Finally, we solve the inverse design problem of determining the geometric parameters for the optimal geometric and mechanical response of these extreme structures

M.M. Bandi, A. Concha, R. Wood, and L. Mahadevan, "A pendulum in a flowing soap film", Physics of Fluids, 25, 041702 (2013).

We consider the dynamics of a pendulum made of a rigid ring attached to an elastic filament immersed in a flowing soap film. The system shows an oscillatory instability whose onset is a function of the flow speed, length of the supporting string, the ring mass, and ring radius. We characterize this system and show that there are different regimes where the frequency is dependent or independent of the pendulum length depending on the relative magnitude of the added-mass. Although the system is an infinite-dimensional, we can explain many of our results in terms of a one degree-of-freedom system corresponding to a forced pendulum.

Indeed, using the vorticity measured via particle imaging velocimetry allows us to make the model quantitative, and a comparison with our experimental results shows we can capture the basic phenomenology of this system.

J.S. Biggins, B. Saintyves, Z. Wei, E. Bouchard, and L. Mahadevan ,"Digital instability of a confined elastic meniscus", Proceedings of the National Academy of Sciences (USA), 110, 12545-12548 (2013).

Thin soft elastic layers serving as joints between relatively rigid bodies may function as sealants, thermal, electrical, or mechanical insulators, bearings, or adhesives. When such a joint is stressed, even though perfect adhesion is maintained, the exposed free meniscus in the thin elastic layer becomes unstable, leading to the formation of spatially periodic digits of air that invade the elastic layer, reminiscent of viscous fingering in a thin fluid layer. However, the elastic instability is reversible and rate-independent, disappearing when the joint is unstressed. We use theory, experiments, and numerical simulations to show that the transition to the digital state is sudden (first-order), the wavelength and amplitude of the fingers are proportional to the thickness of the elastic layer, and the required separation to trigger the instability is inversely proportional to the in-plane dimension of the layer. Our study reveals the energetic origin of this instability and has implications for the strength of polymeric adhesives; it also suggests a method for patterning thin films reversibly with any arrangement of localized fingers in a digital elastic memory, which we confirm experimentally.

A. Shyer, T. Tallinen, N. Nerurkar, Z. Wei, E. Kim, D. Kaplan, C. Tabin and L. Mahadevan, "Villification: how the gut gets its villi", Science, 342, 212-218 (2013).

The villi of the human and chick gut are formed in similar stepwise progressions, wherein the mesenchyme and attached epithelium first fold into longitudinal ridges, then a zigzag pattern, and lastly individual villi. We find that these steps of villification depend on the sequential differentiation of the distinct smooth muscle layers of the gut, which restrict the expansion of the growing endoderm and mesenchyme, generating compressive stresses that lead to their buckling and folding. A quantitative computationalmodel, incorporating measured properties of the developing gut, recapitulates the morphological patterns seen during villification in a variety of species. These results provide a mechanistic understanding of the formation of these elaborations of the lining of the gut, essential for providing sufficient surface area for nutrient absorption.

D. Richter, F-R. Matuschka, A. Spielman, and L. Mahadevan, "How ticks get under your skin: insertion mechanics of the feeding apparatus of Ixodes ricinus ticks", Proceedings of the Royal Society B, 280, 20131758 (2013).

The tick Ixodes ricinus uses its mouthparts to penetrate the skin of its host and to remain attached for about a week, during which time Lyme disease spirochaetes may pass from the tick to the host. To understand how the tick achieves both tasks, penetration and attachment, with the same set of implements, we recorded the insertion events by cinematography, interpreted the mouthparts' function by scanning electron microscopy and identified their points of articulation by confocal microscopy. Our structural dynamic observations suggest that the process of insertion and attachment occurs via a ratchet-like mechanism with two distinct stages. Initially, the two telescoping chelicerae pierce the skin and, by moving alternately, generate a toehold. Subsequently, a breaststroke-like motion, effected by simultaneous flexure and retraction of both chelicerae, pulls in the barbed hypostome. This combination of a flexible, dynamic mechanical ratchet and a static holdfast thus allows the tick to solve the problem of

how to penetrate skin and also remain stuck for long periods of time.

E.H. Yong, D.R. Nelson, and L. Mahadevan "Elastic platonic shells", Physical Review Letters, 111, 177801, (2013).

On microscopic scales, the crystallinity of flexible tethered or cross-linked membranes determines their mechanical response. We show that by controlling the type, number, and distribution of defects on a spherical elastic shell, it is possible to direct the morphology of these structures. Our numerical simulations show that by deflating a crystalline shell with defects, we can create elastic shell analogs of the classical platonic solids. These morphologies arise via a sharp buckling transition from the sphere which is strongly hysteretic in loading or unloading. We construct a minimal Landau theory for the transition using quadratic and cubic invariants of the spherical harmonic modes. Our approach suggests methods to engineer shape into soft spherical shells using a frozen defect topology.

O. Campàs, T. Mammoto, S. Hasso, R.A. Sperling, D. O'Connell, A.G. Bischof, R. Maas, D.A. Weitz, L. Mahadevan & D.E. Ingber , "Quantifying cell-generated mechanical forces within living embryonic tissues" Nature Methods, doi:10.1038/nmeth.2761 (2013).

Cell-generated mechanical forces play a critical role during tissue morphogenesis and organ formation in the embryo. Little is known about how these forces shape embryonic organs, mainly because it has not been possible to measure cellular forces within developing three-dimensional (3D) tissues *in vivo*. We present a method to quantify cell-generated mechanical stresses exerted locally within living embryonic tissues, using fluorescent, cell-sized oil microdroplets with defined mechanical properties and coated with adhesion receptor ligands. After a droplet is introduced between cells in a tissue, local stresses are determined from droplet shape deformations, measured using fluorescence microscopy and computerized image analysis. Using this method, we quantified the anisotropic stresses generated by mammary epithelial cells cultured within 3Daggregates, and we confirmed that these stresses (3.4 $nNmm^{-2}$) are dependent on myosin IIactivity and are more than twofold larger than stresses generated by cells of embryonic tooth mesenchyme, either within cultured aggregates or in developing whole mouse mandibles.

H.V. Prentice-Mott, C-H Chang, L. Mahadevan, T.J. Mitchison, D. Irimia, and J.V. Shah, "Biased migration of confined neutrophil-like cells in asymmetric hydraulic environments" Proceedings of the National Academy of Sciences (USA), 110, 21006-21110 (2013).

Cells integrate multiple measurement modalities to navigate their environment. Soluble and substrate-bound chemical gradients and physical cues have all been shown to influence cell orientation and migration. Here we investigate the role of asymmetric hydraulic pressure in directional sensing. Cells confined in microchannels identified and chose a path of lower hydraulic resistance in the absence of chemical cues. In a bifurcating channel with asymmetric hydraulic resistances, this choice was preceded by the elaboration of two leading edges with a faster extension rate along the lower resistance channel. Retraction of the "losing" edge appeared to precipitate a final choice of direction. The pressure differences altering leading edge protrusion rates were small, suggesting weak force generation by leading edges. The response to the physical asymmetry was able to override a dynamically generated chemical cue.

Motile cells may use this bias as a result of hydraulic resistance, or "barotaxis," in concert with chemotaxis to navigate complex environments.

J.E. Longley, L. Mahadevan and M.K. Chaudhury, “How a blister heals”, Europhysics Letters, 104, 46002, 2013.

We use experiments to study the dynamics of the healing of a blister, a localized bump in a thin elastic layer that is adhered to a soft substrate everywhere except at the bump. We create a blister by gently placing a glass cover slip on a PDMS substrate. The pressure jump across the elastic layer drives fluid flow through micro-channels that form at the interface between the layer and the substrate; these channels coalesce at discrete locations as the blister heals and eventually disappear at a lower critical radius. The spacing of the channel follows a simple scaling law that can be theoretically justified, and the kinetics of healing is rate limited by fluid flow, but with a non-trivial dependence on the substrate thickness that likely arises due to channelization. Our study is relevant to a variety of soft adhesion scenarios.

Presentations: (selected from over 15 invited presentations)

- April 2012, “Continuum and statistical mechanics of ribbons, “ Colloquium Ehrenfestii, Institut Lorentz, Leiden, Netherlands.
- May 2012, “On growth and form,” Niven Lecture, University of British Columbia and Pacific Institute for Mathematical Sciences
- November 2012, “On growth and form: mathematics, physics and biology,” Young Lecture, University of Maryland.
- September 2013, “On growth and form: mathematics, physics and biology,” Simons Foundation MPE Lecture, Brown University.

Katia Bertoldi

Assistant Professor in Applied Mechanics

School of Engineering and Applied Sciences

The overarching goal of Bertoldi's research group is to contribute to the fundamental understanding of the non-linear response of materials and structures.

While engineering applications often use stiff and almost rigid materials, materials capable of undergoing large deformations like elastomers and gels are ubiquitous in daily life and nature. An exciting field of engineering is emerging that uses these compliant materials to design a new class of active devices, such as actuators, adaptive optical systems and self-regulating fluidics.

Bertoldi's research group exploits the non-linear behavior of highly deformable structures to create a new class of adaptive materials that use large deformations and dramatic geometric rearrangements induced by instabilities to rapidly tune their functionalities. Topological changes associated with instabilities are intentionally pursued as an effective approach for tuning the macroscopic response of the structure.

Possible and exciting applications include the design of novel materials with adaptive wave propagation characteristics, reversible encapsulation systems, active materials for on-demand drug delivery, robots that can squeeze themselves through small openings and into tight places and materials with unusual properties such as negative Poisson's ratio.

List of papers acknowledging the Kavli Foundation with abstracts appended

Casadei F, Bertoldi K, Clarke DR. Finite element study of multi-modal vibration damping for thermal barrier coating applications. Computational Materials Science. 2013;79:908-917.

> A physically-based computational model is developed to predict the damping behavior of oxide thermalbarrier coating systems. The constitutive damping model is derived from the theory of point defect relax-ation in crystalline solids and implemented within a finite element framework. While oxide coatings havebeen primarily employed as thermal barriers for gas turbine blades, there is a growing interest in devel-oping multifunctional coatings combining thermal protection and damping capabilities. The direct fre-quency response method, as well as the modal strain energy method, have been implemented toevaluate the functional dependance of damping on temperature and frequency. Numerical results are val-idated through the limited experimental data available in the literature, and new results are presented toillustrate the effects of different topcoat oxides. The paper also illustrates how the developed methodol-ogy enables the damping capacity under different vibrational modes to be predicted, and to estimate the sensitivity of the design for varying geometrical parameters. Finally, the computational model is applied to investigate the damping performance of an oxide-coated turbine blade

Henann DL, Chester SA, Bertoldi K. Modeling of dielectric elastomers: Design of actuators and energy harvesting devices. Journal of the Mechanics and Physics of Solids. 2013;61(10):2047-2066.

Dielectric elastomers undergo large deformations in response to an electric field and consequently have attracted significant interest as electromechanical transducers. Applications of these materials include actuators capable of converting an applied electric field into mechanical motion and energy harvesting devices that convert mechanical energy into electrical energy. Numerically based design tools are needed to facilitate the development and optimization of these devices. In this paper, we report on our modeling capability for dielectric elastomers. We present the governing equations for the electro-mechanically coupled behavior of dielectric elastomers in a thermodynamic frameworkand discuss the attendant finite-element formulation and implementation, using acommercial finite-element code. We then utilize our simulation capability to design and optimize complex dielectric elastomeric actuators and energy harvesting devices invarious settings.

Wang P, Shim J, Bertoldi K. Effects of Geometric and Material Non-linearities on the Tunable Response of Phononic Crystals. Physical Review B. 2013;88:014304.

We investigate the effects of geometric and material nonlinearities introduced by deformation on the linear dynamic response of two-dimensional phononic crystals. Our analysis not only shows that deformation can be effectively used to tune the band gaps and the directionality of the propagating waves, but also reveals how geometric and material nonlinearities contribute to the tunable response of phononic crystals. Our numerical study provides a better understanding of the tunable response of phononic crystals and opens avenues for the design of systems with optimized properties and enhanced tenability.

Babaee S, Shim J, Weaver JC, Patel N, Bertoldi K. 3D Soft Metamaterials with Negative Poisson's Ratio. Advanced Materials. 2013;25(36):5044-5049.

Buckling is exploited to design a new class of three-dimensional metamaterials with negative Poisson's ratio. A library of auxetic building blocks is identified and procedures are defined to guide their selection and assembly. The auxetic properties of these materials are demonstrated both through experiments and finite element simulations and exhibit excellent qualitative and quantitative agreement.

Shim J, Shan S, Kosmrlj A, Kang SH, Chen ER, Weaver JC, Bertoldi K. Harnessing instabilities for design of soft reconfigurable auxetic/chiral materials. Soft Matter. 2013;9(34):8198-8202.

Most materials have a unique form optimized for a specific property and function. However, the ability to reconfigure material structures depending on stimuli opens exciting opportunities. Although mechanical instabilities have been traditionally viewed as a failure mode, here we exploit them to design a class of 2D soft materials whose architecture can be dramatically changed in response to an external stimulus. By considering geometric constraints on the tessellations of the 2D Euclidean plane, we have identified four possible periodic distributions of uniform circular holes where mechanical instability can be exploited to reversibly switch between expanded (i.e. with circular holes) and compact (i.e. with elongated, almost closed elliptical holes) periodic configurations. Interestingly, in all these structures buckling is found to induce large negative values of incremental Poisson's ratio and in two of them also the formation of chiral patterns. Using a combination of finite element simulations and experiments at the centimeter scale we demonstrate a proof-of-concept of the

proposed materials. Since the proposed mechanism for reconfigurable materials is induced by elastic instability, it is reversible, repeatable and scale-independent.

Kang SH, Shan S, Noorduin WL, Khan M, Aizenberg J, Bertoldi K. Buckling-Induced Reversible Symmetry Breaking and Amplification of Chirality Using Supported Cellular Structures. Advanced Materials. 2013;25(24):3380-3385.

Buckling-induced reversible symmetry breaking and amplification of chirality using macro- and microscale supported cellular structures is described. Guided by extensive theoretical analysis, cellular structures are rationally designed, in which buckling induces a reversible switching between achiral and chiral configurations. Additionally, it is demonstrated that the proposed mechanism can be generalized over a wide range of length scales, geometries, materials, and stimuli.

Su T, Wicks N, Pabon J, Bertoldi K. Mechanism by which a frictionally confined rod loses stability under initial velocity and position perturbations. International Journal ofSolids and Structures. 2013;50:2468-2476.

We present a theory to reveal for the first time the distinct mechanisms by which a compressed rod con-fined in a channel buckles in the presence of dry friction. Contrary to the case of a frictionless contact, with friction the system can bear substantially enhanced compressive load without buckling after its stiffness turns negative, and the onset of instability is strongly affected by the amount of perturbation set by the environment. Our theory, confirmed by simulations, shows that friction enhances stability by opening a wide stable zone in the perturbation space. Buckling is initiated when the applied compressive force is such that the boundary of the stable zone touches a point set by the environment, at a much higher critical load. Furthermore, our analysis shows that friction has a strong effect on the buckling mode; an increase in friction is found to lead to higher buckling modes.

Rudykh S, Bertoldi K. Stability of anisotropic magnetorheological elastomers in finite deformations: A micromechanical approach. Journal of the Mechanics and Physics of Solids.2013;61:949-967.

We study the stability of magnetorheological elastomers (MREs) undergoing finite deformations in the presence of a magnetic field and derive a general condition for the onset of macroscopic instabilities. In particular, we focus on anisotropic MREs with magnetoactive particles that are aligned along a particular direction, forming chain-like structures. We idealize the microstructure of such anisotropic magnetosensitive elasto-mers as a multilayered structure and derive an analytical model for the behavior of these materials. The analytical model, together with the derived condition for the onset of instabilities, is used to investigate the influence of magnetomechanical finite deforma-tions on the stability of the anisotropic MREs. While the formulation is developed for generic hyperelastic magnetosensitive elastomers, the results are presented for a special class of soft materials incorporating a neo-Hookean hyperelastic response. The influence of material properties and loading conditions is investigated, providing a detailed picture of the possible failure modes.

Presentations

- APS March Meeting, Baltimore
- ASME Annual Meeting, San Diego
- MRS Fall Meeting, Boston
- SES, Providence
- Georgia Tech, Aerospace Department
- MIT, Mechanical Engineering Department
- John Hopkins University, Mechanical Engineering Department
- Northwstern University, Mechanical Engineering Department
- Rensselaer Polytechnic Institute, Mechanical Engineering Department
- UIUC, Civil Engineering Department
- The University of Texas at Austin, Aerospace Department

KIBST-related activities

Participated in the Kavli Nano-Nexus Conference at the Gran Melia Resort, Puerto Rico.

Zhigang Suo

Allen E. and Marilyn M. Puckett Professor of Mechanics and Materials

School of Engineering and Applied Sciences

Zhigang Suo studies the mechanical behavior of materials and structures. Basic processes include fracture, deformation, polarization, and diffusion, driven by various thermodynamic forces (e.g., stress, electric field, electron wind, chemical potential). Applications are concerned with microelectronics, large-area electronics, soft materials, active materials, and lithium-ion batteries. Soft materials can undergo large and reversible deformation in response to diverse stimuli. For example, an electric field can cause an elastomer to stretch several times its length. As another example, a change in pH can cause a gel to swell many times its volume. These soft active materials are being developed for wide-ranging applications, including soft robots, tunable optics, and self-regulating fluidics. Recent research highlights include giant deformation induced by electrical voltage, exceptionally tough and stretchable hydrogels, and highly transparent and stretchable actuators and loudspeakers.

List of papers acknowledging the Kavli Foundation with abstracts appended

B. Dong, H. Cai, G. I. Ng,1 P. Kropelnicki, J. M. Tsai, A. B. Randles, M. Tang, Y. D. Gu, Z. G. Suo, A. Q. Liu. A nanoelectromechanical systems actuator driven and controlled by Q-factor attenuation of ring resonator. Applied Physics Letters 103, 181105 (2013).

> In this Letter, an optical gradient force driven Nanoelectromechanical Systems (NEMS) actuator, which is controlled by the Q-factor attenuation of micro-ring resonator, is demonstrated. The actuator consists of a tunable actuation ring resonator, a sensing ring resonator, and a mechanical actuation arc. The actuation displacement can reach up to 14 nm with NEMS actuator include single molecule manipulation, nano-manipulation, and high sensitivity sensors.

Matt Pharr, Zhigang Suo, Joost J. Vlassak. Measurements of the Fracture Energy of Lithiated Silicon Electrodes of Li-ion Batteries. Nano Letters 13, 5570-5577(2013).

> We have measured the fracture energy of lithiated silicon thin-film electrodes as a function of lithium concentration. To this end, we have constructed an electro-chemical cell capable of testing multiple thin-film electrodes in parallel. The stress in the electrodes is measured during electrochemical cycling by the substrate curvature technique. The electrodes are disconnected one by one after delithiating to various states of charge, that is, to various concentrations of
> lithium. The electrodes are then examined by optical microscopy to determine when cracks first form. All of the observed cracks appear brittle in nature. By determining the condition for crack initiation, the fracture energy is calculated using an analysis from fracture mechanics. In the same set of experiments, the fracture energy at a second state of charge (at small concentrations of lithium) is measured by determining the maximum value of the stress during delithiation. The silicon and is essentially independent of the concentration of lithium.

Thus, lithiated silicon demonstrates a unique ability to flow plastically and fracture in a brittle manner.

Tongqing Lu, Shengqiang Cai, Huiming Wang, Zhigang Suo. Computational model of deformable lenses actuated by dielectric elastomers. Journal of Applied Physics 114, 104104 (2013).

A recent design of deformable lens mimics the human eye, adjusting its focal length in response to muscle-like actuation. The artificial muscle is a membrane of a dielectric elastomer subject to a voltage. Here, we calculate the coupled and inhomogeneous deformation of the lens and the dielectric elastomer actuator by formulating a nonlinear boundary-value problem. We characterize the strain-stiffening elastomer with the Gent model and describe the voltage-induced deformation using the model of ideal dielectric elastomer. The computational predictions agree well with experimental data. We use the model to explore the space of parameters, including the prestretch of the membrane, the volume of the liquid in the lens, and the size of the dielectric elastomer actuator relative to the lens. We examine how various modes of failure limit the minimum radius of curvature.

Canhui Yang, Meixiang Wang, Hussain Haider, Jianhai Yang, Jeong-Yun Sun, Yongmei Chen, Jinxiong Zhou, Zhigang Suo. Strengthening alginate/polyacrylamide hydrogels using various multivalent cations. ACS Applied Materials and Interfaces 5, 10418-10422(2013).

We successfully synthesized a family of alginate/polyacrylamide hydrogels using various multivalent cations. These hydrogels exhibit exceptional mechanical properties. In particular, we discovered that the hydrogels cross-linked by trivalent cations are much stronger than those cross-linked by divalent cations. We demonstrate stretchability and toughness of the hydrogels by inflating a hydrogel sheet into a large balloon, and the elasticity by using a hydrogel block as a vibration isolator in a forced vibration test. The excellent mechanical properties of these hydrogels may open up applications for hydrogels.

Widusha R. K. Illeperuma, Jeong-Yun Sun, Zhigang Suo, Joost J. Vlassak. Force and stroke of a hydrogel actuator. Soft Matter 9, 8504-8511 (2013).

Hydrogels that undergo a volume phase transition in response to an external stimulus are of great interest because of their possible use as actuator materials. The performance of an actuator material is normally characterized by its force–stroke curve, but little is known about the force–stroke behavior of hydrogels. We use the theory of the ideal elastomeric gel to predict the force–stroke curves of a temperature- sensitive hydrogel and introduce an experimental method for measuring the curve. The technique is applied to PNIPAm hydrogels with low cross-link densities. The maximum force generated by the hydrogel increases with increasing cross-link density, while the maximum stroke decreases. The force– stroke curves predicted by the theory of the ideal elastomeric gel are in very good agreement with the experimental curves.

Qihan Liu, Agathe Robisson, Yucun Lou, Zhigang Suo. Kinetics of swelling under constraint. Journal of Appllied Physics 114, 064901 (2013).

Swellable elastomers are used to seal flow channels in oilfield operations. After sealing, the elastomers are constrained triaxially, and a contact load builds up between the elastomers and surrounding rigid materials. For these applications, the ability to predict the evolution of the contact load is important. This work introduces an experimental setup to measure the contact load as a function of time. The experimental data are well represented by a simple time-relaxation equation derived from the linear poroelastic theory, enabling a determination of the effective diffusivity of solvent inside the elastomers.

Christoph Keplinger, Jeong-Yun Sun, Choon Chiang Foo, Philipp Rothemund, George M. Whitesides, Zhigang Suo. Stretchable, transparent, ionic conductors. Science 341, 984-987 (2013).

Existing stretchable, transparent conductors are mostly electronic conductors. They limit the performance of interconnects, sensors, and actuators as components of stretchable electronics and soft machines. We describe a class of devices enabled by ionic conductors that are highly stretchable, fully transparent to light of all colors, and capable of operation at frequencies beyond 10 kilohertz and voltages above 10 kilovolts. We demonstrate a transparent actuator that can generate large strains and a transparent loudspeaker that produces sound over the entire audible range. The electromechanical transduction is achieved without electrochemical reaction. The
ionic conductors have higher resistivity than many electronic conductors; however, when large stretchability and high transmittance are required, the ionic conductors have lower sheet resistance than all existing electronic conductors.

Max Darnell, Jeong-Yun Sun, Manav Mehta, Chris Johnson, Praveen Arany, Zhigang Suo, David Mooney. Performance and biocompatibility of extremely tough alginate/polyacrylamide hydrogels. Biomaterials 34, 8042-8048 (2013).

Although hydrogels now see widespread use in a host of applications, low fracture toughness and brittleness have limited their more broad use. As a recently described interpenetrating network (IPN) of alginate and polyacrylamide demonstrated a fracture toughness of w9000 culture and in vivo conditions. These hydrogels can sustain a compressive strain of over 90% with minimal loss of Young's Modulus as well as minimal swelling for up to 50 days of soaking in culture conditions. Mouse mesenchymal stem cells exposed to the IPN gel-conditioned media maintain high viability, and although cells exposed to conditioned media demonstrate slight reductions in proliferation and metabolic activity (WST assay), these effects are abrogated in a dose-dependent manner. Implantation of these IPN hydrogels into subcutaneous tissue of rats for 8 weeks led to mild fibrotic encapsulation and minimal inflammatory response. These results suggest the further exploration of extremely tough alginate/PAAM IPN hydrogels as biomaterials.

Jeong-Yun Sun, Nanshu Lu, Kyu-Hwan Oh, Zhigang Suo, Joost J. Vlassak. Islands stretch test for measuring the interfacial fracture energy between a hard film and a soft substrate. Journal of Applied Physics 113, 223702 (2013).

We present a technique for measuring the interfacial fracture energy, Γ_i , between a hard thin film and a soft substrate. A periodic array of hard thin islands is fabricated on a soft substrate, which is then subjected to uniaxial tension under an optical microscope. When the applied strain reaches a critical value, delamination between the islands and the substrate starts from the edge of the islands. As the strain is increased, the interfacial cracks grow in a stable fashion. At a given applied strain, the width of the delaminated region is a unique function of the interfacial fracture energy. We have calculated the energy release rate driving the delamination as a function of delamination width, island size, island thickness, and applied strain. For a given materials system, this relationship allows determination of the interfacial fracture energy from a measurement of the delamination width. The technique is demonstrated by measuring the interfacial fracture energy of plasma-enhanced chemical vapor deposition SiN_x islands on a polyimide substrate. We anticipate that this technique will find application in the flexible electronics industry where hard islands on soft substrates are a common architecture to protect active devices from fracture.

Jiangshui Huang, Samuel Shian, Zhigang Suo, David R. Clarke. Maximizing the energy density of dielectric elastomer generators using equi-biaxial loading. Advanced Functional Materials 23, 5056-5061 (2013).

Dielectric elastomer generators (DEGs) for harvesting electrical energy from mechanical work have been demonstrated but the energy densities achieved are still small compared with theoretical predictions. In this study, significant improvements in energy density (560 J/kg with a power density of 280 W/ kg and an efficiency of 27%) are achieved using equi-biaxial stretching, a mechanical loading configuration that maximizes the capacitance changes. The capacitance of dielectric elastomers subjected to equi-biaxial stretches is demonstrated to be proportional to the fourth power of the stretch. Quanti- fication of the individual energy contributions indicates that attaining higher conversion efficiencies is limited by viscous losses within the acrylic elas- tomer, suggesting that still higher conversion efficiencies with other elasto- mers should be attainable with our novel mechanical loading design.

H. Vandeparre, Qihan Liu, I.R. Minev, Zhigang Suo, Stephanie Lacour. Localization of folds and cracks in thin metal films coated on flexible elastomer foams. Advanced Materials 25, 3117-3121 (2013). http://www.seas.harvard.edu/suo/papers/304.pdf

(no abstract)

Ekin D. Cubuk, Wei L. Wang, Kejie Zhao, Joost J. Vlassak, Zhigang Suo, Efthimios Kaxiras. Morphological evolution of Si nanowires upon lithiation: a first-principles multiscale model. Nano Letters 13, 2011-2015 (2013).

Silicon is a promising anode material for high-capacity Li-ion batteries. Recent experiments show that lithiation of crystalline silicon nanowires leads to highly anisotropic morphologies.

This has been interpreted as due to anisotropy in equilibrium interface energies, but this interpretation does not capture the dynamic, nonequilibrium nature of the lithiation process. Here, we provide a comprehensive explanation of experimentally observed morphological changes, based on first-principles multiscale simulations. We identify reaction paths and associated structural transformations for Li insertion into the Si {110} and {111} surfaces and calculate the relevant energy barriers from density functional theory methods. We then perform kinetic Monte Carlo simulations for nanowires with surfaces of different orientations, which reproduce to a remarkable degree the experimentally observed profiles and the relative reaction front rates.

Alessia Romeo, Qihan Liu, Zhigang Suo, Stephanie Lacour. Elastomeric substrates with embedded stiff plateforms for stretchble electrodes. Applied Physics Letters 102, 131904 (2013).

Stretchable electronics typically integrate hard, functional materials on soft substrates. Here we report on engineered elastomeric substrates designed to host stretchable circuitry. Regions of a stiff material, patterned using photolithography, are embedded within a soft elastomer leaving a smooth surface. We present the associated design rules to produce stretchable circuits based on experimental as well as modeling data. We demonstrate our approach with thin-film electronic materials. The “customized” elastomeric substrates may also be used as a generic elastic substrate for stretchable circuits prepared with alternative technologies, such as transfer-printing of inorganic, thinned devices.

Min Ren, Jianguo Huang, Hong Cai, Julius M. Tsai, Jinxiong Zhou, Zishun Liu,Zhigang Suo, Aiqun Liu. Nano-opto-mechanical actuator and pull-back instability. ACS Nano 7, 1676-1681 (2013).

This paper studies the nonlinear behavior of a nano-optomechanical actuator, consisting of a free-standing arc in a ring resonator that is coupled to a bus waveguide through evanescent waves. The arc deflects when a control light of a fixed wavelength and optical power is pumped into the bus waveguide, while the amount of deflection is monitored by measuring the transmission spectrum of a broadband probe light. This nanoactuator achieves a maximal deflection of 43.1 nm, with a resolution of 0.28 nm. The optical force is a nonlinear function of the deflection of the arc, leading to pull-back instability when the control light is red-tuned. This instability is studied by a combination of experiment and modeling. Potential applications of the nanoactuator include bio-nanomotor, optical switches, and optomechanical memories.

Philseok Kim, Yuhang Hu, Jack Alvarenga, Mathias Kolle, Zhigang Suo, Joanna Aizenberg. Rational design of mechano-responsive optical materials by fine tuning the evolution of strain-dependent wrinkling patterns. Advanced Optical Materials 1, 381-388 (2013).

Rational design strategies for mechano-responsive optical material systems are created by introducing a simple experimental system that can continu- ously vary the state of bi-axial

stress to induce various wrinkling patterns, including stripes, labyrinths, herringbones, and rarely observed checker- boards, that can dynamically tune the optical properties. In particular, a switching of two orthogonally oriented stripe wrinkle patterns from oxidized polydimethylsiloxane around the critical strain value is reported, as well as the coexistence of these wrinkles forming elusive checkerboard patterns, which are predicted only in previous simulations. These strain-induced wrinkle patterns give rise to dynamic changes in optical transmittance and diffraction patterns. A theoretical description of the observed pattern forma- tion is presented which accounts for the residual stress in the membrane and allows for the fine-tuning of the window of switching of the orthogonal wrinkles. Applications of wrinkle-induced changes in optical properties are demonstrated, including a mechanically responsive instantaneous privacy screen and a transparent sheet that reversibly reveals a message or graphic and dynamically switches the transmittance when stretched and released.

Laurence Brassart, Zhigang Suo. Reactive flow in solids. Journal of the Mechanics and Physics of Solids 61, 61–77 (2013).

When guest atoms diffuse into a host solid and react, the host may flow inelastically. Often a reaction can stimulate flow in a host too brittle to flow under a mechanical load alone. We formulate a theory of reactive flow in solids by regarding both flow and reaction as nonequilibrium processes, and placing the driving forces for flow and reaction on equal footing. We construct chemomechanical rate-dependent kinetic models without yield strength. In a host under constant stress and chemical potential, flow will persist indefinitely, but reaction will arrest. We also construct chemomechanical yield surface and flow rule by extending the von Mises theory of plasticity. We show that the host under a constant deviatoric stress will flow gradually in response to ramp chemical potential, and will ratchet in response to cyclic chemical potential.

Laurence Brassart, Kejie Zhao, Zhigang Suo. Cyclic plasticity and shakedown in high-capacity electrodes of lithium-ion batteries. International Journal of Solids and Structures 50, 1120-1129 (2013).

Of all materials, silicon has the highest capacity to store lithium, and is being developed as an electrode for lithium-ion batteries. Upon absorbing a large amount of lithium, the electrode swells greatly, with a volumetric change up to 300%. The swelling is inevitably constrained in practice, often leading to stress and fracture. Evidence has accumulated that the swelling-induced stress can be partially relieved by plas- tic flow, and that electrodes of small feature sizes can survive many cycles of lithiation and delithiation without fracture. Here we simulate a particle of an electrode subject to cyclic lithiation and delithiation. A recently developed theory of concurrent large swelling and finite-strain plasticity is used to co-evolve fields of stress, deformation, concentration of lithium, and chemical potential of lithium. We identify three types of behavior. When the yield strength is high and the charging rate is low, the entire particle deforms elastically in all cycles. When the yield strength is low and the charging rate is high, the particle (or part of it) undergoes cyclic plasticity. Under intermediate conditions, the particle exhibits the shake- down behavior: part of the particle flows plastically in a certain number of initial cycles, and then the entire particle remains elastic in subsequent cycles. We

discuss the effect of the three types of behavior on the capacity and the electrochemical efficiency.

Francois Weiss, Shengqiang Cai, Yuhang Hu, Min Kyoo Kang, Rui Huang, Zhigang Suo. Creases and wrinkles on the surface of a swollen gel. Journal of Applied Physics 114, 073507 (2013).

Consider a layer of a gel attached to a rigid substrate, immersed in a solvent, and swelling in the thickness direction. The flat surface of the gel remains stable if the swelling ratio is small, but becomes unstable if the swelling ratio is large. While creases have been commonly observed, wrinkles have also been observed under certain conditions. We compare the critical conditions for the onset of creases and wrinkles by using a nonlinear field theory of gels. The critical swelling ratio for the onset of creases is calculated by using a finite element method, and that for wrinkles is calculated by using an analytical method. We find that the critical swelling ratio for the onset of creases is significantly lower than that for wrinkles.

Ramses V. Martinez, Jamie L. Branch, Carina R. Fish, Lihua Jin, Robert F. Shepherd, Zhigang Suo, and George M. Whitesides. Robotic tentacles with three-dimensional mobility based on flexible elastomers. Advanced Materials 25, 205-212 (2013).

(no abstract)

Nicolas Zalachas, Shengqiang Cai, Zhigang Suo, Yuri Lapusta. Crease in a ring of a pH-sensitive hydrogel swelling under constraint. International Journal of Solids and Structures 50, 920-927 (2013).

When a hydrogel swells, its surface often forms creases, a type of localized instability that nucleates and propagates in the form of self-contact. Motivated by recent applications of pH-sensitive hydrogels as actuators in adaptive lenses, here we analyze creases induced by constrained swelling. A ring of a gel, bonded between two rigid plates, swells by absorbing a solution from its external wall. The amount of swelling is adaptive in response to the change of the pH of the external solution. We analyze the large and inhomogeneous deformation in the gel by using a previously developed nonlinear field theory and finite element method. We show that, as the pH in the external solution increases, a short ring swells smoothly, but a tall ring forms a crease. We further show that the large deformation and instability can significantly affect the functionality of the adaptive lenses.

Presentations

- December 13, 2013, Soft materials and soft machines. Seminar, Mechanical Engineering Department, Boston University. Host: Harold Park

- December 2, 2013, Stretchable ionics. Symposium TT Transport Properties in Nanocomposites, MRS Fall Meeting, Boston. Invited by Haleh Ardebili.

- November 21, 2013, Artificial muscles and artificial nerves for soft machines. Seminar, Mechanical and Aerospace Engineering Department. The University of Californian San Diego San Diego. Host: Shengqiang Cai and Xanthippi Markenscoff.

- November 20, 2013, "Rheology of creases—recent computation and experiment." Keynote at the symposium on Multiphysics Simulations and Experiments for Solids. Invited by Herold Park

- November 18, 2013, "Theory and experiments on the poroelasticity and viscoelasticity of elastomeric hydrogels." Keynote at the symposium on the Mechanics of Gels. Invited by Hanqing Jiang

- November 18, 2013, "Stretchable Ionic Conductors as Artificial Neurons for Soft Machines." Invited presentation in honor of the Drucker Medalist Professor Yonggang Huang. Invited by Pradeep Sharma.

- October 3, 2013, "Highly stretchable and tough hydrogels." Seminar, Institute for High Performance Computing. Host: Yong Wei Zhang

- October 2, 2013, "Soft machines." Seminar. School of Electrical and Electronic Engineering . Host: Ai Qun Liu

- October 2, 2013, "Soft materials and soft machines." Plenary lecture. 23rd International Workshop on Computational Mechanics of Materials. Host: Adrian Koh

- September 30, 2013, "Soft materials and soft machines." Seminar, Engineering Science Program, National University of Singapore. Host: Adrian Koh

- September 23, 2013, "Soft machines." Distinguished Lecture Series, Department of Mechanical and Process Engineering, ETH Zurich. Host: Edoardo Mazza

- June 17, 2013, "Rheology of creases." Professor Anthony G. Evans Memorial Symposium. 13th International Conference on Fracture. Beijing, Invited by Bill Curtin.

- June 16, 2013, "Soft machines." International Symposium on New Frontiers in Mechanics and Materials Research. Tsinghua University, Invited by Yonggang Huang and Huajian Gao.

- June 6, 2013, "Mechanics of hydrogels." The Viggo Tvergaard Symposium: New Horizons of Materials Mechanics. Copenhagen. Invited by Christian F. Niordson.

- May 30, 2013, "Highly stretchable and tough hydrogels." Seminar, ESPCI ParisTech. Host Costantino Creton.

- May 24, 2013, "Soft active materials and soft machines." Seminar, ESPCI ParisTech. Host Costantino Creton.

- April 24, 2013, "Soft active materials and soft machines." Seminar, Chemical and Biological Engineering Department, Princeton University. Host: Ilhan Aksay.

- April 3, 2013, "Highly stretchable and tough hydrogels." Invited talk. Symposium NN Multifunctional Biomaterials. MRS Spring Meeting. San Francisco. Organizers: Andreas Lendlein, Mei Wei, Zhiyuan Zhong, Thao Nguyen.

- March 22, 2013, "Electromechanical instability in soft materials: theory, experiments and applications." Invited session on Elastic instabilities and pattern formation in structureless solids. American Physical Society March Meeting, Baltimore. Invited by Benny Davidovitch.

- March 15, 2013, "Mechanics of hydrogels". 54th New England Complex Fluids Workshop. Yale University. Invited by Eric Dufresne.

- February 6, 2013, "Extremely stretchable and tough hydrogels". Squishy Physics Seminars. Hosts: Adrian Pegoraro and Assaf Rotem, Weitz Lab at Harvard University.

- January 22, 2013, "Soft generators that harvest energy from renewable sources". Arthur Newell Talbot Lecture. Invited by Placid Ferreira, Head of the Department of Mechanical Science and Engineering, The University of Illinois, Urbana-Champaign. Faculty hosts: Harley Johnson and Ken Christensen.

- January 9, 2013, "Extremely stretchable and tough hydrogels". Invited talk. Gordon Research Conferences on Macromolecular Materials. Ventura. Invited by Alfred J. Crosby.

Radhika Nagpal

Fred Kavli Professor of Computer Science

School of Engineering and Applied Sciences

Radhika Nagpal's work lies on the boundary of artificial intelligence, robotics, and biology. Her research interest is in self-organizing multi-agent systems, where large numbers of simple agents cooperate to produce complex and robust global behavior. She studies bio-inspired programming paradigms for designing collective intelligence in robotics and sensor-actuator networks, drawing inspiration mainly from multicellular biology and social insects. Her most recent work involved developing collective robotic systems that mimic social insect colonies, e.g. a termite-inspired climbing robots that build large scale structures, and a programmable thousand robot collective that can be used to simulate tasks achieved by ant collectives. She has also worked on models of self-organization in biology, specifically how cells in the Drosophila wing self-assemble to create wing structure.

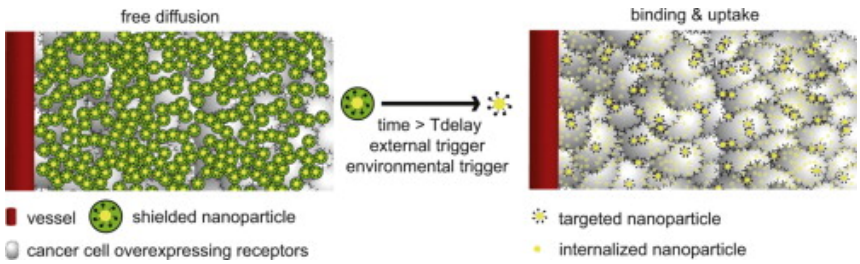
During her sabbatical she worked with entomologists to develop a deeper understanding of cooperation in insect societies. On the theoretical side, a common theme in all of her work is mathematically understanding the relationship between local behavior and emergent global behavior.

List of papers acknowledging the Kavli Foundation with abstracts appended

S. Hauert, S. Berman, R.Nagpal, S. N. Bhatia , "A computational framework for identifying design guidelines to increase the penetration of targeted nanoparticles into tumors," Nano Today, Dec 2013.

Targeted nanoparticles are increasingly being engineered for the treatment of cancer. By design, they can passively accumulate in tumors, selectively bind to targets in their environment, and deliver localized treatments. However, the penetration of targeted nanoparticles deep into tissue can be hindered by their slow diffusion and a high binding affinity. As a result, they often localize to areas around the vessels from which they extravasate, never reaching the deep-seeded tumor cells, thereby limiting their efficacy. To increase tissue penetration and cellular accumulation, we propose generalizable guidelines for nanoparticle design and validate them using two different computer models that capture the potency, motion, binding kinetics, and cellular internalization of targeted nanoparticles in a section of tumor tissue. One strategy that emerged from the models was delaying nanoparticle binding until after the nanoparticles have had time to diffuse deep into the tissue. Results show that nanoparticles that are designed according to these guidelines do not require fine-tuning of their kinetics or size and can be administered in lower doses than classical targeted nanoparticles for a desired tissue penetration in a large variety of tumor scenarios. In the future, similar models could serve as a testbed to explore engineered tissue-distributions that arise when large numbers of nanoparticles interact in a tumor environment.

Graphical abstract



N. Napp, R. Adams, "Message Passing Inference with Chemical Reaction Networks," Advances in Neural Information Processing Systems (NIPS), Dec 2013.

(no abstract)

A. Becker, G. Habibi, J. Werfel, M. Rubenstein, J. McLurkin, "Massive Uniform Manipulation: Controlling Large Populations of Simple Robots With a Common Input Signal," IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), Nov 2013.

Roboticists, biologists, and chemists are now pro- ducing large populations of simple robots, but controlling large populations of robots with limited capabilities is difficult, due to communication and onboard-computation constraints. Direct human control of large populations seems even more challenging.

In this paper we investigate control of mobile robots that move in a 2D workspace using three different system models. We focus on a model that uses broadcast control inputs specified in the global reference frame.

In an obstacle-free workspace this system model is uncontrol- lable because it has only two controllable degrees of freedom— all robots receive the same inputs and move uniformly. We prove that adding a single obstacle can make the system controllable, for any number of robots. We provide a position control algorithm, and demonstrate through extensive testing with human subjects that many manipulation tasks can be reliably completed, even by novice users, under this system model, with performance benefits compared to the alternate models.

We compare the sensing, computation, communication, time, and bandwidth costs for all three system models. Results are validated with extensive simulations and hardware experiments using over 100 robots.

"M.Rubenstein, A.Cabrera, J. Werfel, G. Habibi, J.McLurkin, R.Nagpal,"Collective Transport of Complex Objects by Simple Robots: Theory and Experiments, Intl. Conf. on Autonomous Agents and Multiagent Systems (AAMAS), May 2013.

Ants show an incredible ability to collectively transport com- plex irregular-shaped objects with seemingly simple coor- dination. Achieving similarly effective collective transport with

robots has potential applications in many settings, from agriculture to construction to disaster relief. In this pa- per we investigate a simple decentralized strategy for collec- tive transport in which each agent acts independently with- out explicit coordination. Using a physics-based model, we prove that this strategy is guaranteed to successfully trans- port a complex object to a target location, even though each agent only knows the target direction and does not know the object shape, weight, its own position, or the position and number of other agents. Using two robot hardware plat- forms, and a wide variety of complex objects, we validate the strategy through extensive experiments. Finally, we present a set of experiments to demonstrate the versatility of the simple strategy, including transport by 100 robots, trans- port of an actively moving object, adaptation to change in goal location, and dealing with partially observable goals.

Robert Wood, Radhika Nagpal, Gu-Yeon Wei , "Flight of the Robobees ," Scientific American, March 2013.

Not too long ago a mysterious affliction called Colony Collapse Disorder (CCD) began to wipe out honeybee hives. These bees are responsible for most commercial pollination in the U.S., and their loss provoked fears that agriculture might begin to suffer as well. In 2009 the three of us, along with colleagues at Harvard University and Northeastern University, began to seriously consider what it would take to create a robotic bee colony. We wondered if mechanical bees could replicate not just an individual's behavior but the unique behavior that emerges out of interactions among thousands of bees. We have now created the first RoboBees—flying bee-size robots—and are working on methods to make thousands of them cooperate like a real hive.

Superficially, the task appears nearly impossible. Bees have been sculpted by millions of years of evolution into incredible flying machines. Their tiny bodies can fly for hours, maintain stability during wind gusts, seek out flowers and avoid predators.

KIBST-related activities

Host the NERC Symposium, October 2013

The Overview of NERC: The Northeast Robotics Colloquium aims to bring together all of the many varieties of robotics practitioners in the northeastern United States, in an event that is simultaneously a research meeting, a networking and job-fair event, and a showcase for established and up-and-coming robotics companies. Ultimately, we hope to promote the kind of healthy and well-connected robotics community that will be essential in fueling the field's rapid growth in the coming decade.

This is the second edition of the Northeast Robotics Colloquium. The first edition of NERC was held at MIT. It saw more than 150 people from 16 universities and 21 companies from the northeast region.

Fellow at Radcliffe College:

“From Social Insects to Radcliffe Fellows: Exploring a Collective Intelligence”

> What do a computer scientist, a playwright, and a biologist have in common? Collective intelligence, as Radhika Nagpal discovered during her year as a fellow at the Radcliffe Institute. She worked with experimental biologists to develop a better understanding of collective intelligence in social insects through the application of computer science. The professor of computer science at Harvard's School of Engineering and Applied Sciences and a faculty member of the Harvard Wyss Institute of Biologically Inspired Engineering also found a surprising commonality with a playwright and other Radcliffe fellows.

https://www.radcliffe.harvard.edu/video/social-insects-radcliffe-fellows-exploring-collective-intelligence