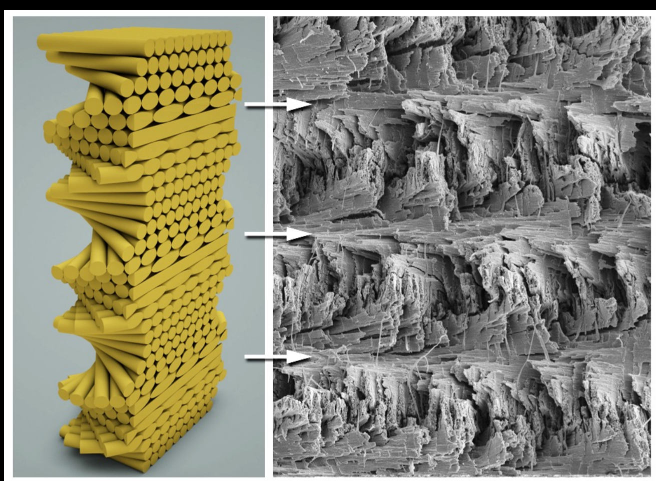
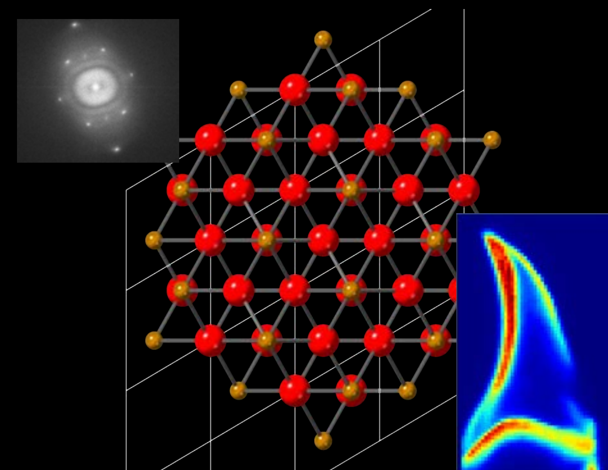
Translation of Biologically-inspired Multifunctional Architected Materials







Kisailus Biomimetic and Nanostructured Materials Lab
University of California at Irvine
Prof. David Kisailus david.k@uci.edu

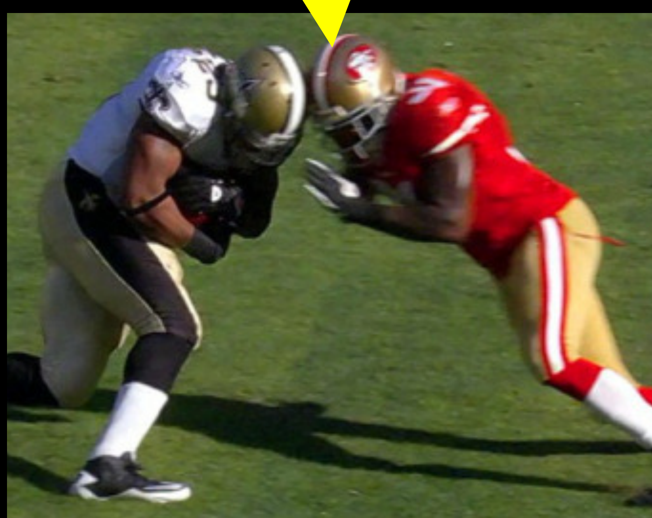
Kisailus Biomimetics and Nanostructured Materials Lab

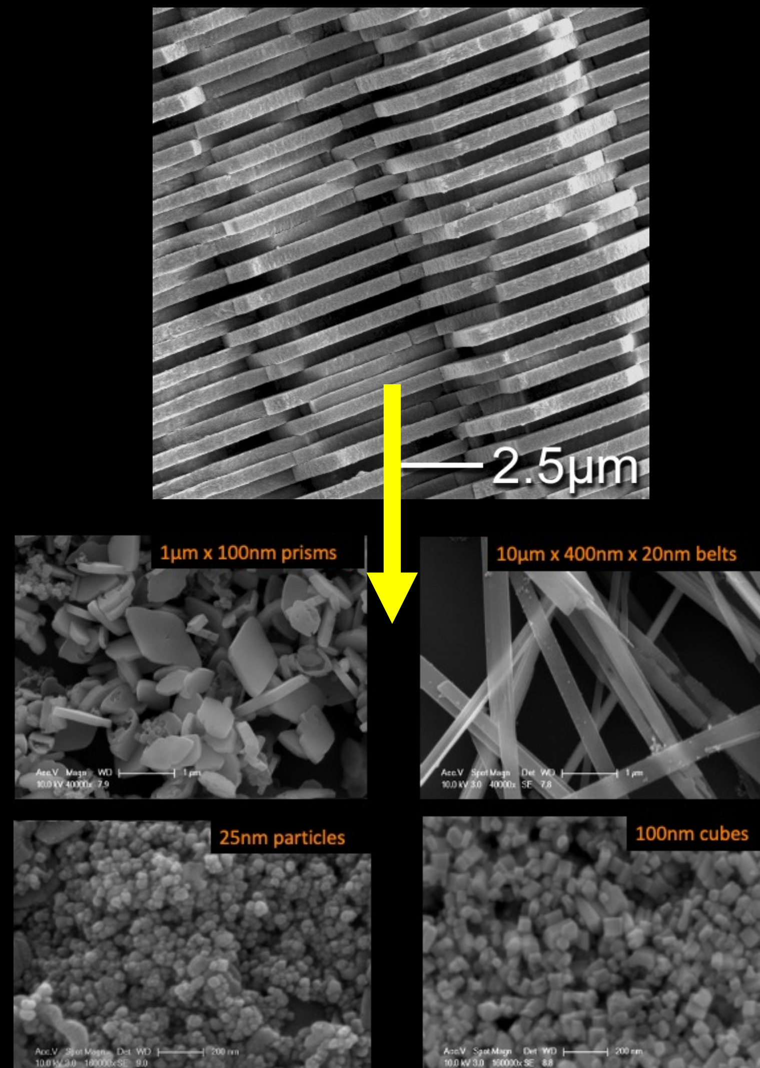
PI: Professor David Kisailus

Team: 2 postdocs, 6 Ph.D. students, 11 undergrads

Fields: Materials Science & Engineering, Molecular, Ecology and Evolutionary Biology, Chemical, Mechanical, & Aerospace Engineering, Organic Chemistry

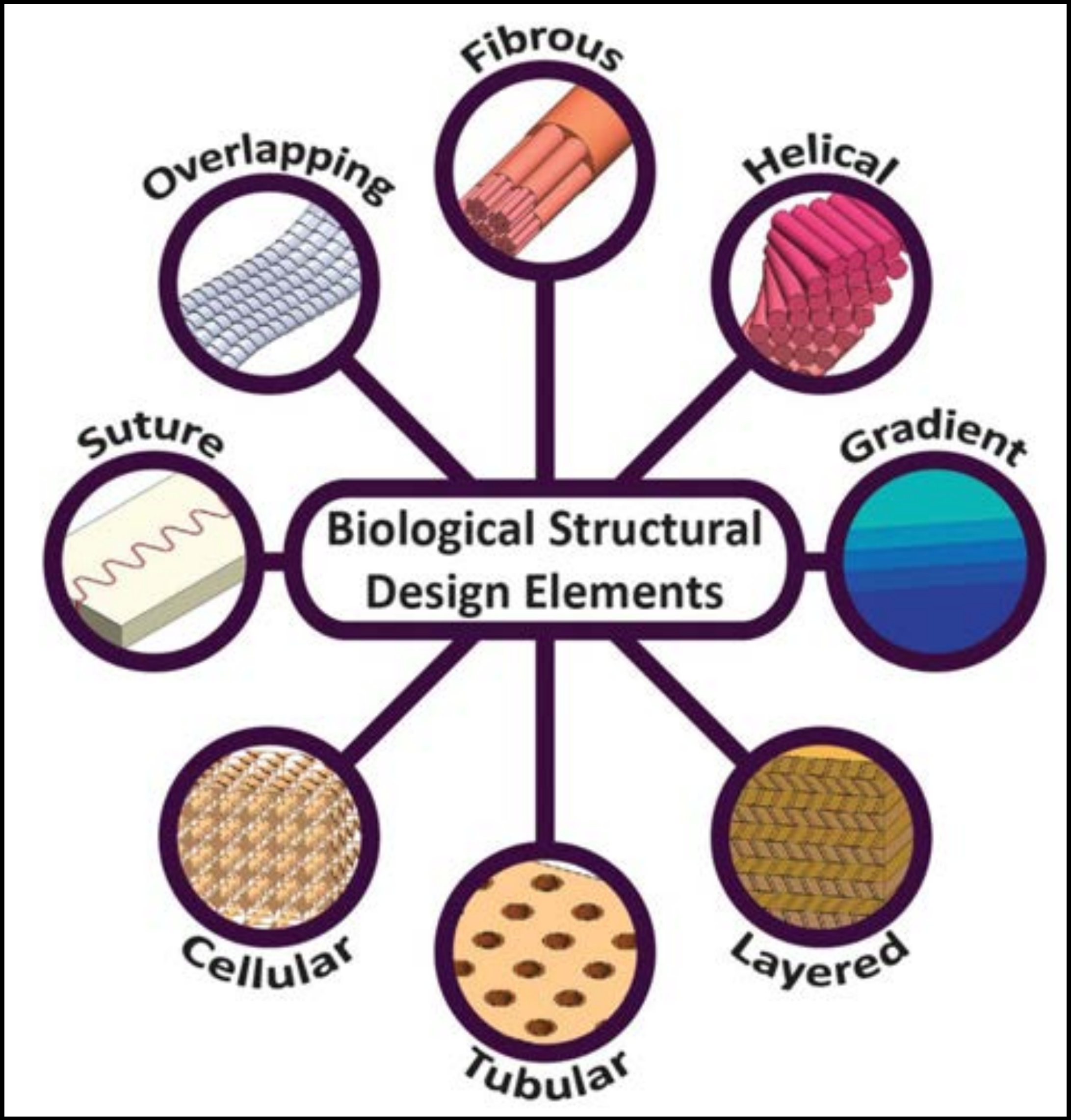
2 Main Thrusts: Biomimetics and Bio-inspired Nanostructured Materials





Nature offers multiple comparatives of tough materials

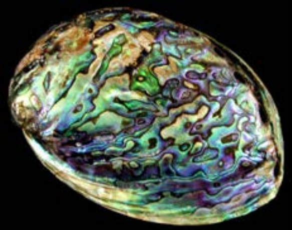
Common Design Themes Identified: Multiple structural design elements from nano – mm scale



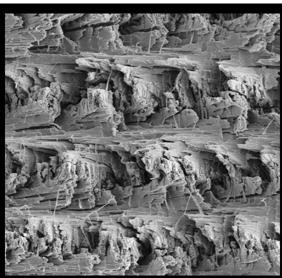




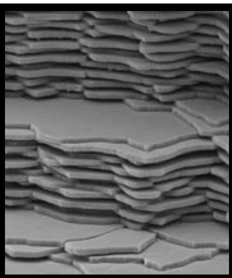


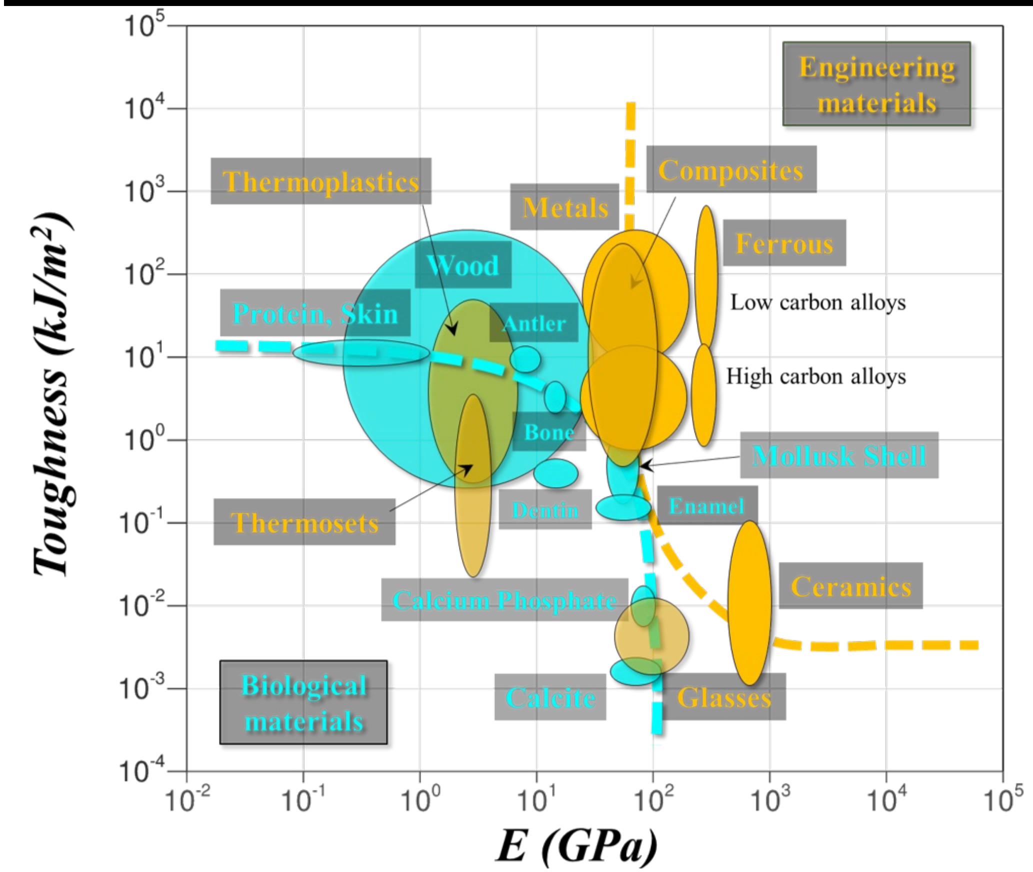


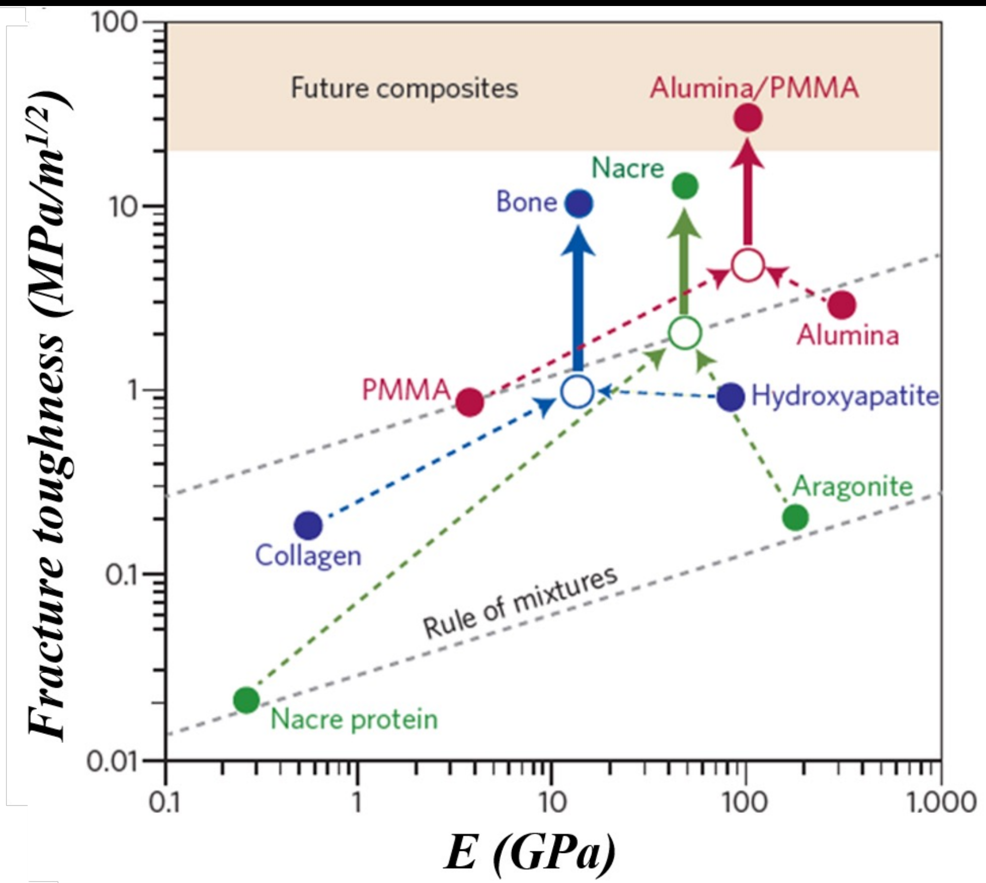

Adapted from Meyers et al. Adv. Mater. **2015**, *27*, 5455–5476



Mechanical Advantages of Natural Materials





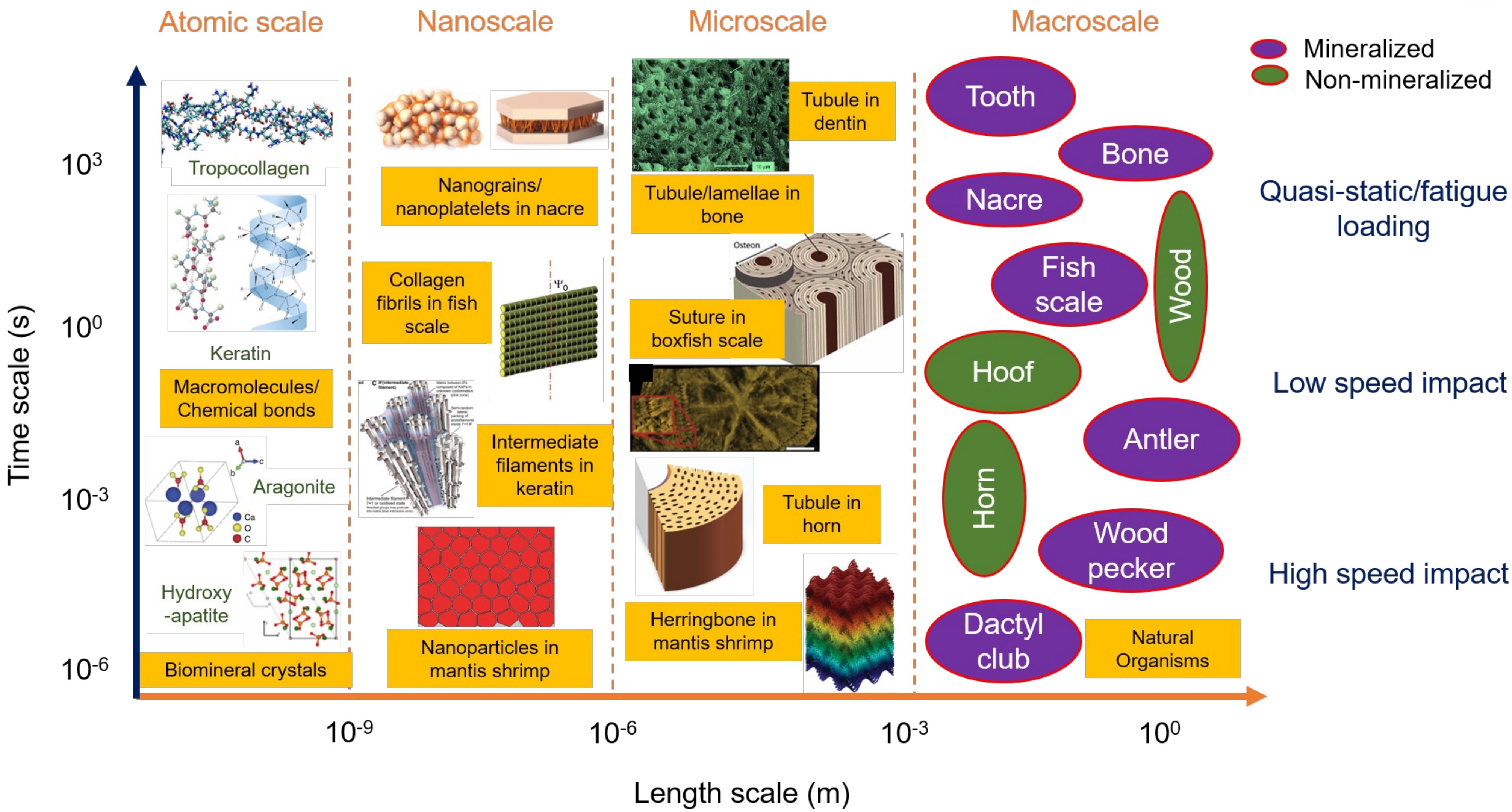


Huang, Kisailus, *et al. Advanced Materials*, 2019

Wegst, Ritchie, *et al.*, *Nature Materials*, 2015

- *Materials toughness and strength are usually mutually exclusive*
- *Biological materials such as bone and nacre show both high strength and toughness*
- *Hierarchical assembly key in maintaining toughness*

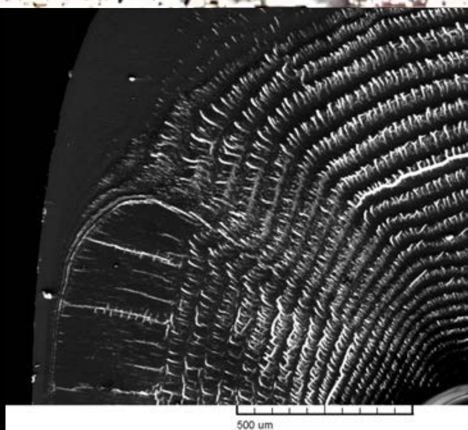
Biological Materials: Multiple structural design elements from nano – mm scale

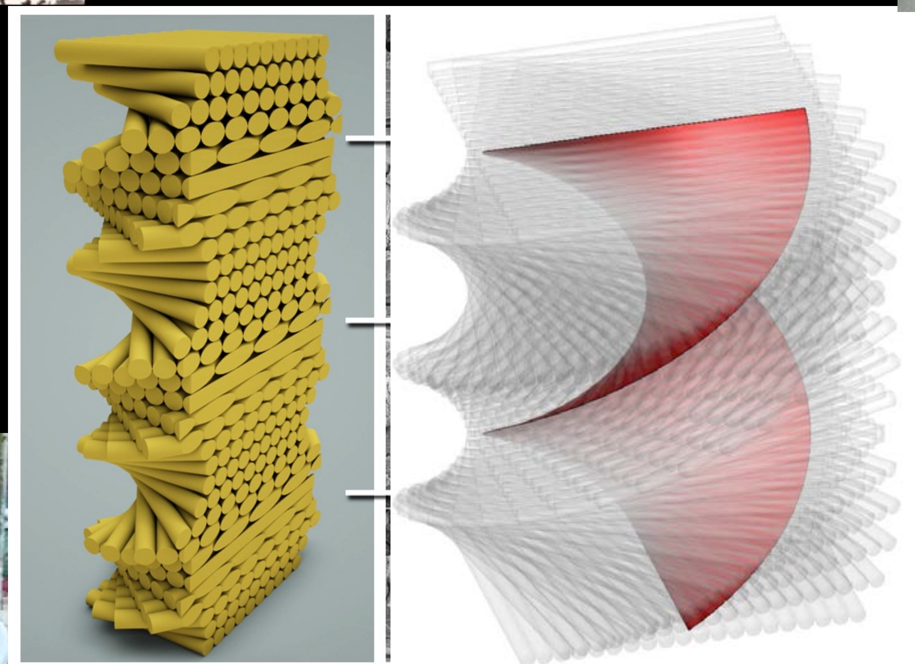


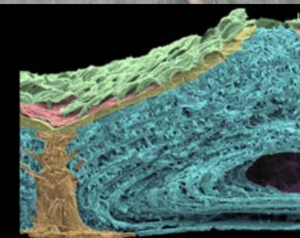
Huang, Ritchie, McKittrick, Zavattieri, Kisailus, *et al. Advanced Materials*, 2019

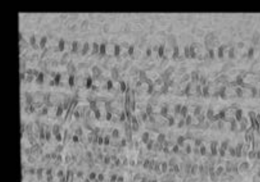
*cited 230+ times – *Review highlighting some of our MURI's major findings*

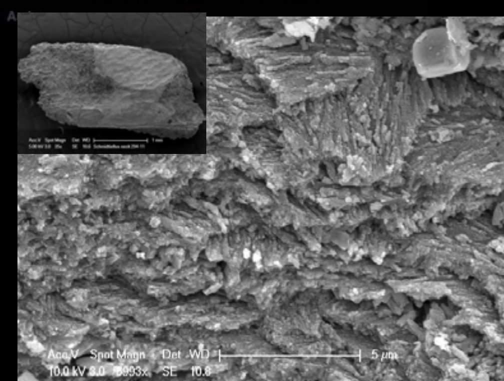
Helicoid: most dominant architecture observed in impact resistant structures for over 500 MYA











Crack deflection occurs at interfaces with significant difference in modulus

Crack twisting enhances toughness!

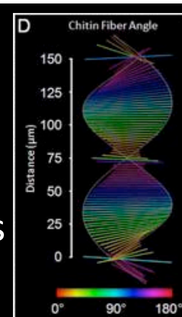
Helicoidal fracture pattern propagating between layers, with a rotating crack front that remains parallel to the fibers without severing them

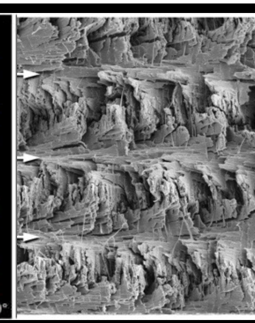
Blueprints for Success: Biology to Engineering –
at the macro and microscale

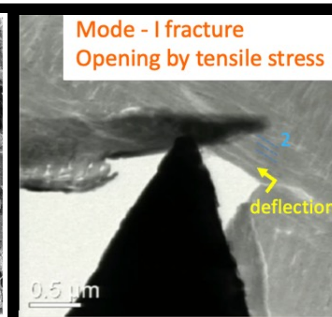
Leverage Successful Biological Adaptations to Reveal New Scientific Mechanisms that Underpin Structure-Function Relationships

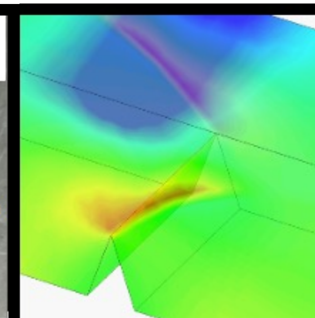
$$$

Materials Scientists
Mechanical Engineers
Physicists



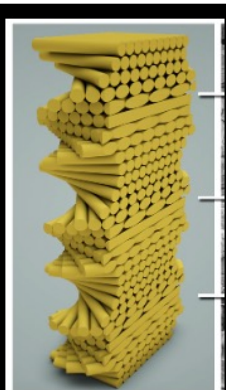




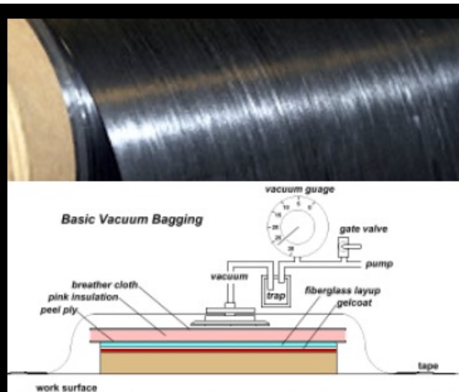


Kisailus et al., *Science*, 336 (2012) 1275-1280

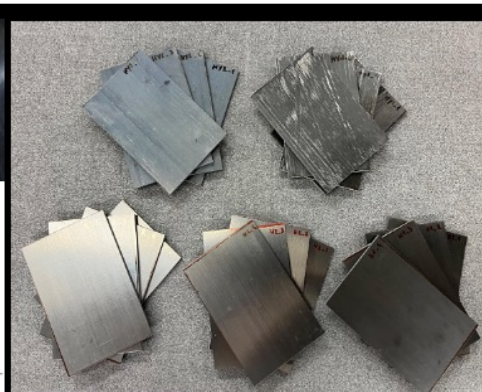
Translate via Biomimicry Towards Advanced Engineered Materials



Biological design

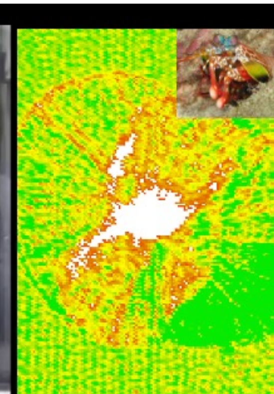


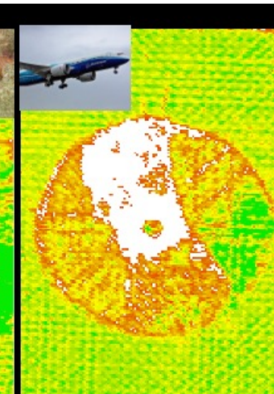
Prepreg processing



Carbon/glass/ceramic fiber

Mechanical Testing





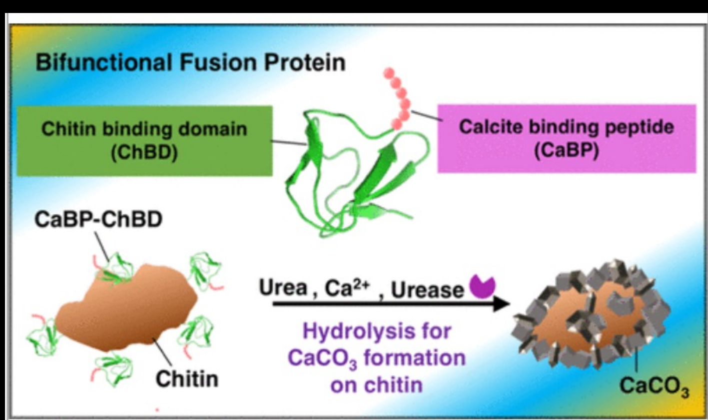
50% Tougher / 20% Stronger vs. Current Aircraft Design

Kisailus et al., *Acta Biomaterialia*, 10 (9) (2014)

Commercialization and Integration into DoD, Auto, Aerospace, Sports Applications

Self Assembled $CaCO_3$-based Helicoids

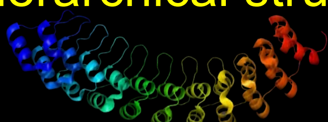
- **Controlled nano structures on solution-processed inorganic/organic film for liquid crystal application**
  Journal of Sol-Gel Science and Technology (IF 2.606) Pub Date: 2022-09-30 , DOI: 10.1007/s10971-022-05940-8
  Dong Hyun Kim, Ju Hwan Lee, Dong Wook Lee, Jin Young Oh, Jonghoon Won, Yang Liu, Dae-Shik Seo
- **The Role of Intrinsically Disordered Proteins in Liquid–Liquid Phase Separation during Calcium Carbonate Biomineralization**
  Biomolecules (IF 6.064) Pub Date: 2022-09-09 , DOI: 10.3390/biom12091266
  Aneta Tarczewska, Klaudia Bielak, Anna Zoglowek, Katarzyna Sołtys, Piotr Dobryszycki, Andrzej Ożyhar, Mirosława Różycka
- **Precipitation of calcium carbonate in the presence of rhamnolipids in alginate hydrogels as a model of biomineralization**
  Colloids and Surfaces B: Biointerfaces (IF 5.999) Pub Date: 2022-08-02 , DOI: 10.1016/j.colsurfb.2022.112749
  Natalia Czaplicka, Donata Konopacka-Łyskawa, Agata Nowotnik, Aleksandra Mielewczyk-Gryń, Marcin Łapiński, Rafał Bray
- **Characteristics of Calcium Carbonate Crystals Mediated Bacillus cereus**
  Geomicrobiology Journal (IF 2.412) Pub Date: 2022-06-15 , DOI: 10.1080/01490451.2022.2087807
  Hatice Aysun Mercimek Takci, Pemra Bakirhan, Kivilcim Caktu Guler
- **Biomineral-Inspired Colloidal Liquid Crystals: From Assembly of Hybrids Comprising Inorganic Nanocrystals and Organic Polymer Components to Their Functionalization**
  Accounts of Chemical Research (IF 24.466) Pub Date: 2022-06-14 , DOI: 10.1021/acs.accounts.2c00063
  Masanari Nakayama, Takashi Kato
- **Effects of Chloride, Sulfate and Magnesium Ions on the Biomineralization of Calcium Carbonate Induced by Lysinibacillus xylanilyticus DB1-12**
  Geomicrobiology Journal (IF 2.412) Pub Date: 2022-06-03 , DOI: 10.1080/01490451.2022.2079776
  Huaxiao Yan, Meiyu Huang, Tiantian Wang, Yudong Xu, Long Meng, Lanmei Zhao, Zuozhen Han, Jihan Wang, Maurice E. Tucker, Hui Zhao
- **Well-ordered nanostructured organic/inorganic hybrid thin film construction via UV nanoimprint lithography applicable to liquid crystal systems**
  Journal of Applied Polymer Science (IF 3.057) Pub Date: 2022-04-18 , DOI: 10.1002/app.52445
  Dong Wook Lee, Jong Hoon Won, Dong Hyun Kim, Jin Young Oh, Dae-Hyun Kim, Yang Liu, Dae-Shik Seo
- **Biomineralization of calcium carbonate under amino acid carbon dots and its application in bioimaging**
  Materials & Design (IF 9.417) Pub Date: 2022-04-09 , DOI: 10.1016/j.matdes.2022.110644
  Zongqi Feng, Tingyu Yang, Tiantian Liang, Zhouying Wu, Ting Wu, Jianbin Zhang, Lan Yu
- **Ion Pathways in Biomineralization: Perspectives on Uptake, Transport, and Deposition of Calcium, Carbonate, and Phosphate**
  Journal of the American Chemical Society (IF 16.383) Pub Date: 2021-12-09 , DOI: 10.1021/jacs.1c09174
  Keren Kahil, Steve Weiner, Lia Addadi, Assaf Gal

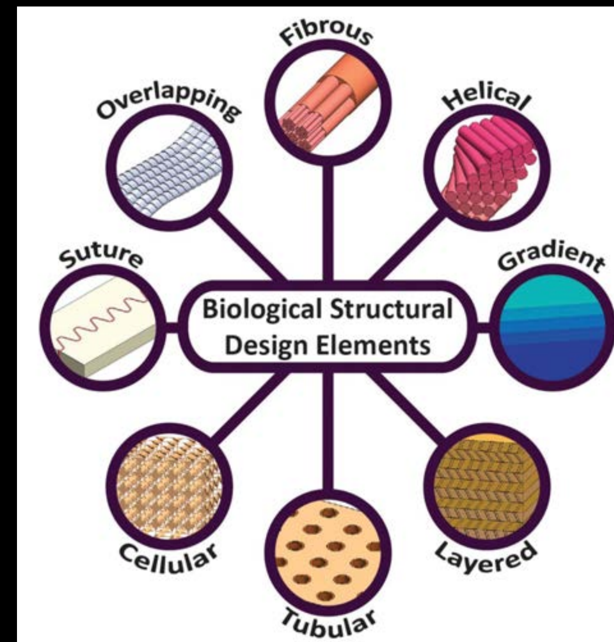


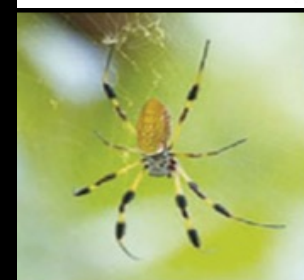
Not scalable – limited materials

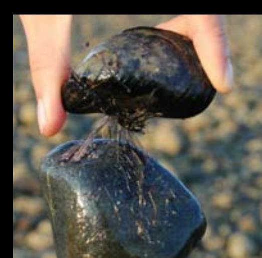
Bio-inspired Multifunctional Architected Materials

- Architectures for light-weight, strong, tough materials
  - Airframes, satellites, counter pressure space suits, exoskeletons
- Development of Multifunctional Structures – nature does this well! We don't!
  - Self-healing, self-cooling
  - Heat dissipation
  - Radiation resistant
  - Adaptive camouflage
  - Multimodal sensing
  - Mechano-chemical sensing
- Implement into soft/hybrid robotic systems
  - Combine multiple features
  - Hierarchical structures









Many interesting and activated features are *mineralized* and at the *meso-nano-atomic scales*

And…how to capture this?

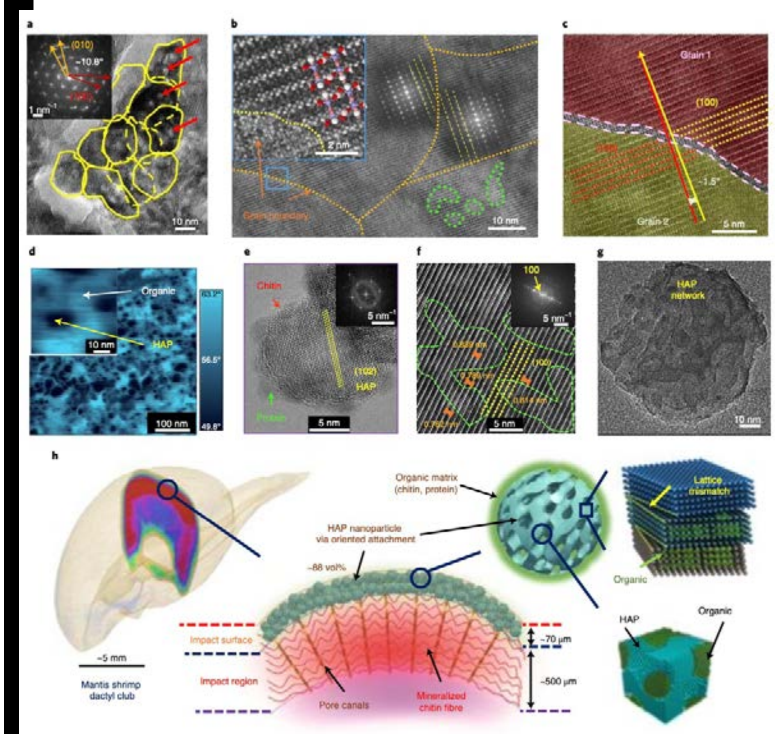
nature materials

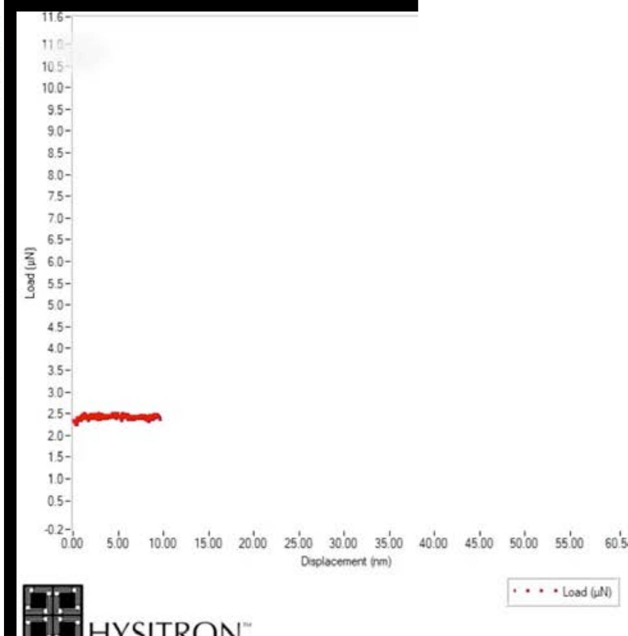
ARTICLES

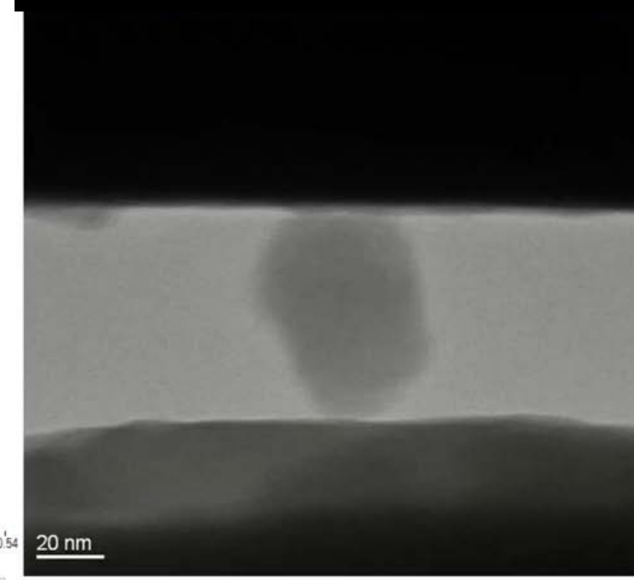
https://doi.org/10.1038/s41563-020-0768-7

A natural impact-resistant bicontinuous composite nanoparticle coating

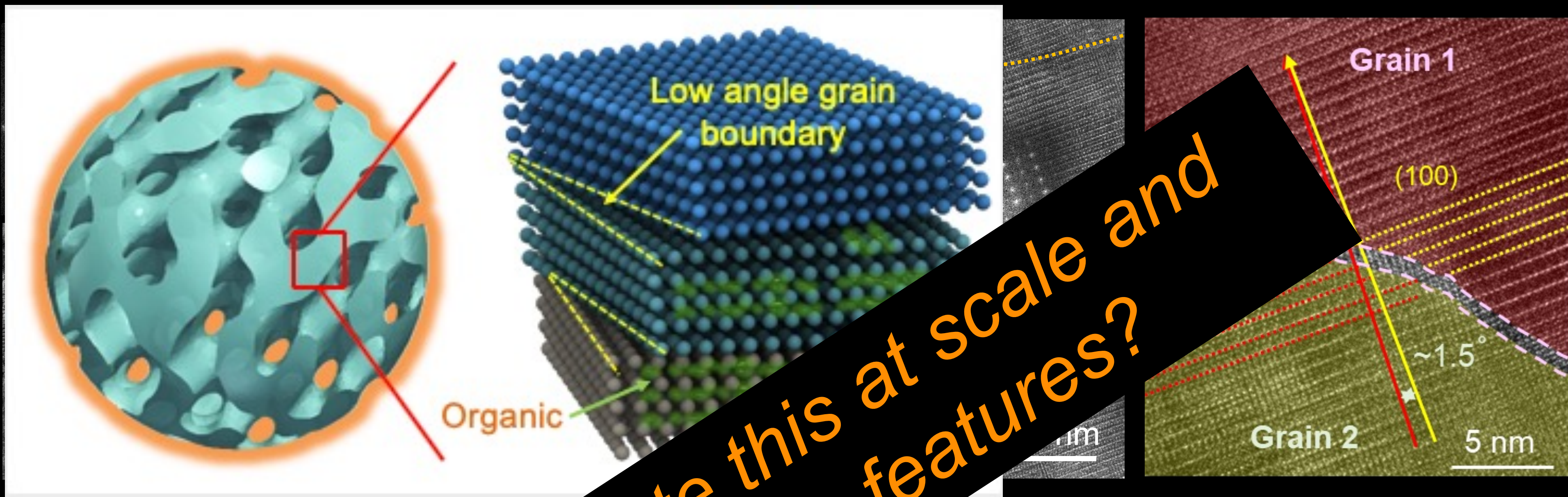
Wei Huang[1,2], Mehdi Shishehbor[3], Nicolás Guarín-Zapata[3], Nathan D. Kirchhofer[4], Jason Li[4], Luz Cruz[5], Taifeng Wang[5], Sanjit Bhowmick[6], Douglas Stauffer[6], Praveena Manimunda[6], Krassimir N. Bozhilov[7], Roy Caldwell[8], Pablo Zavattieri[3] and David Kisailus[1,2,5] ✉



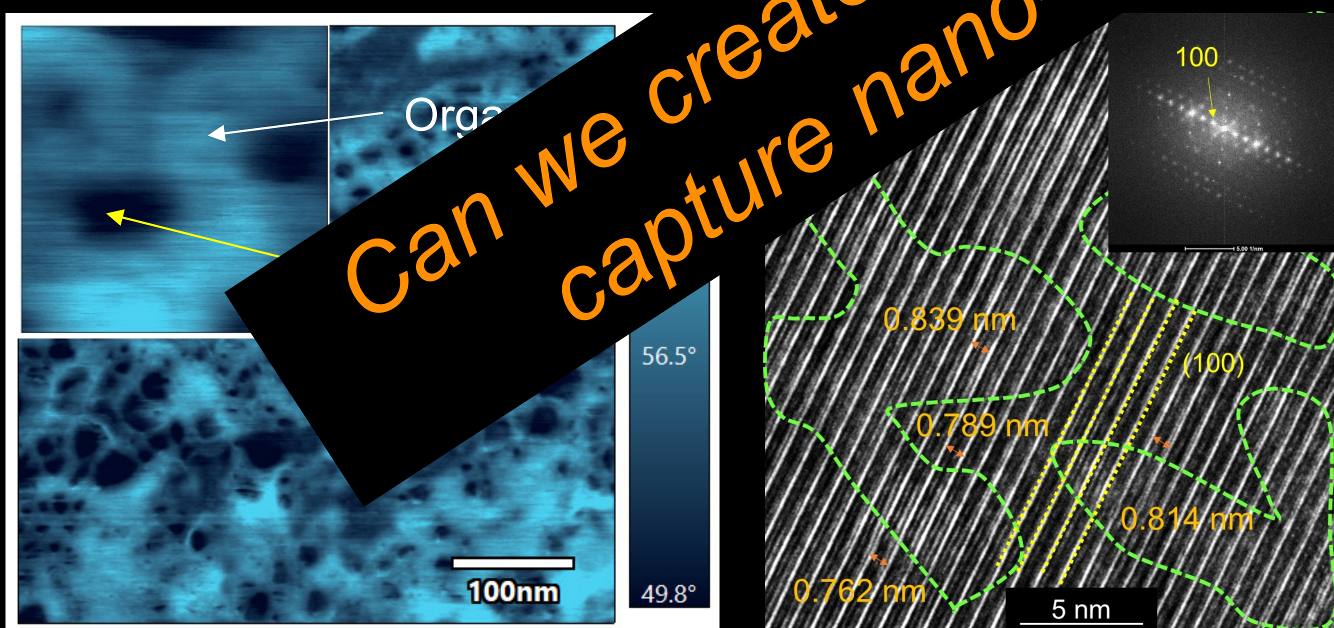




Hierarchically arranged nanoparticle-based coating



Can we create this at scale and capture nano-features?



Mesocrystalline grains that form bi-continuous organic-mineral structures

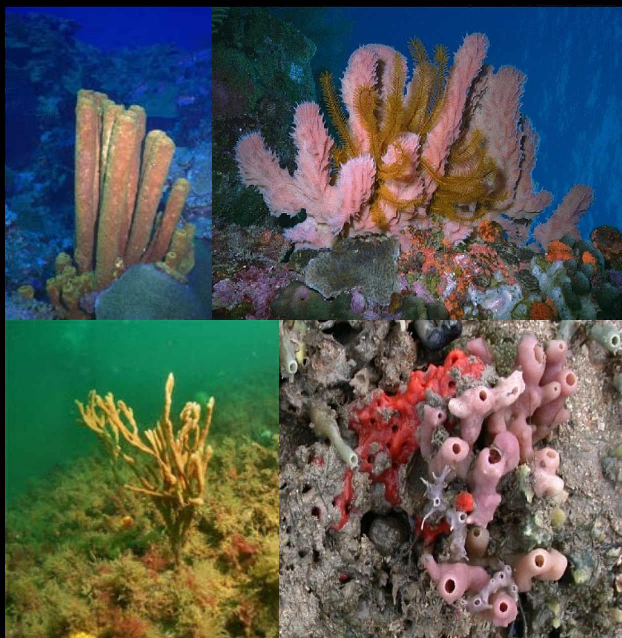
Multiple energy dissipation mechanisms:

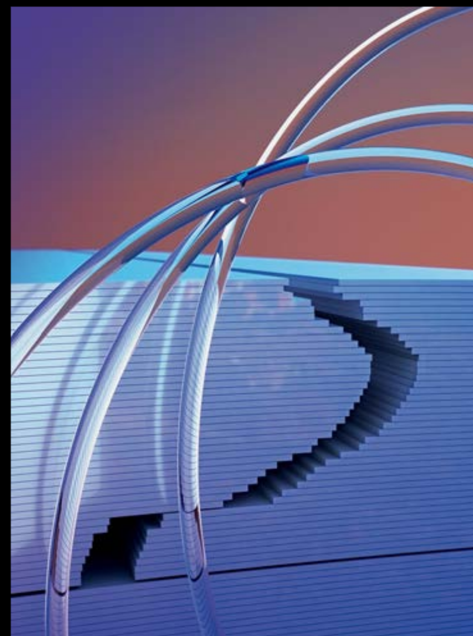
Rotation, translation,
2° particle breakage,
amorphization, dislocations

Kisailus, Zavattieri, *et al.*, *Nature Materials, 19(11):1236-1243*

What can Biology teach us about making new materials?

Synthesis is key:



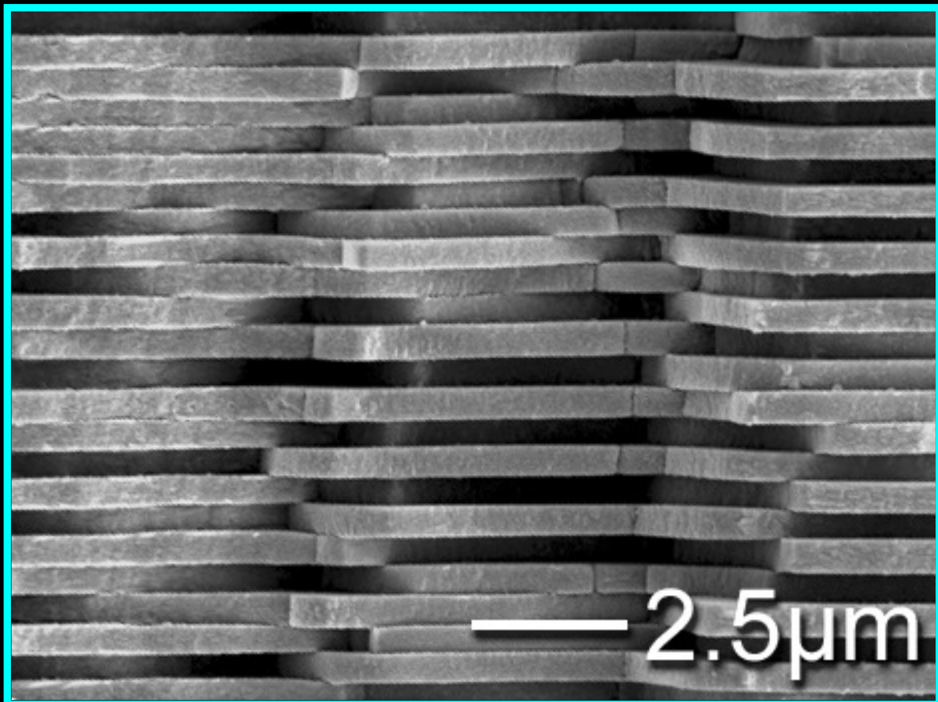


?

- Solution-based low temperature processing
- Controlled nanostructured growth using organics
- Optimized structure to carry out function

- Traditional Engineering materials use high temperature, environmentally unfriendly methods

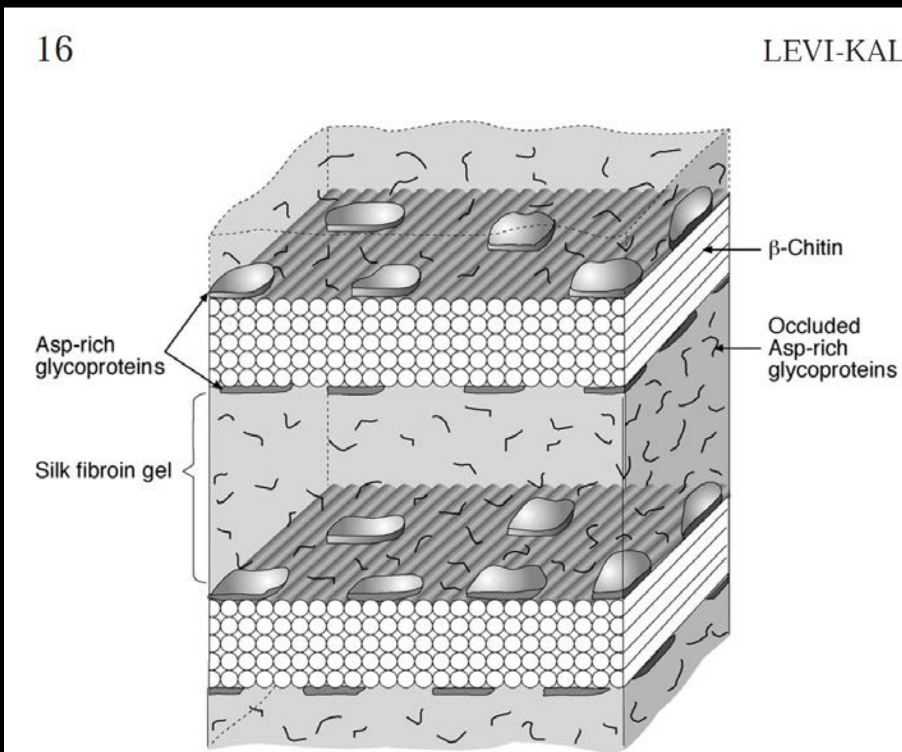
Biological Control (via templating organics, pH control, etc.) Affords Morphologically Unique Structures

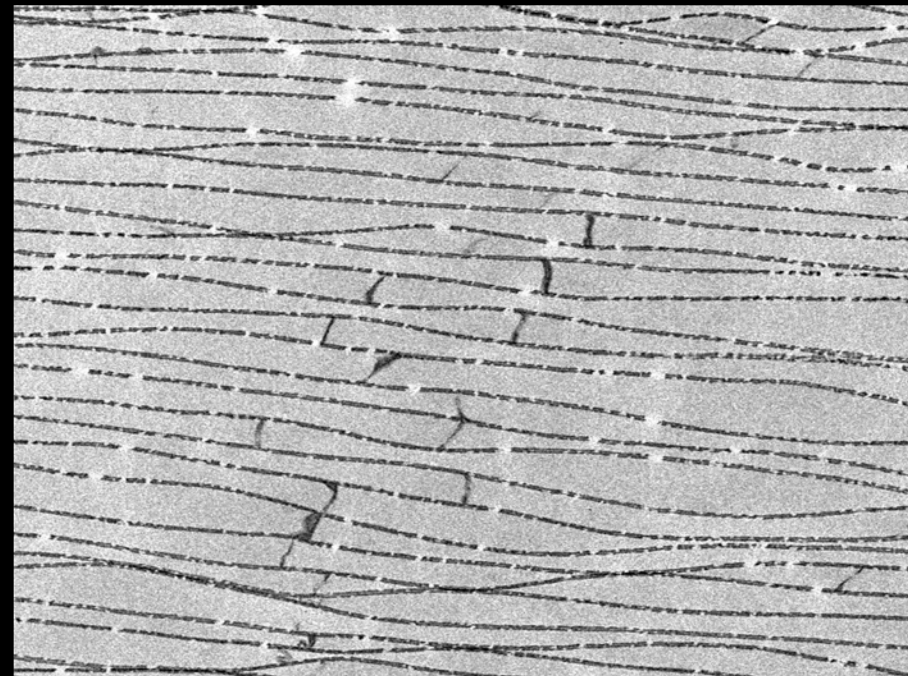


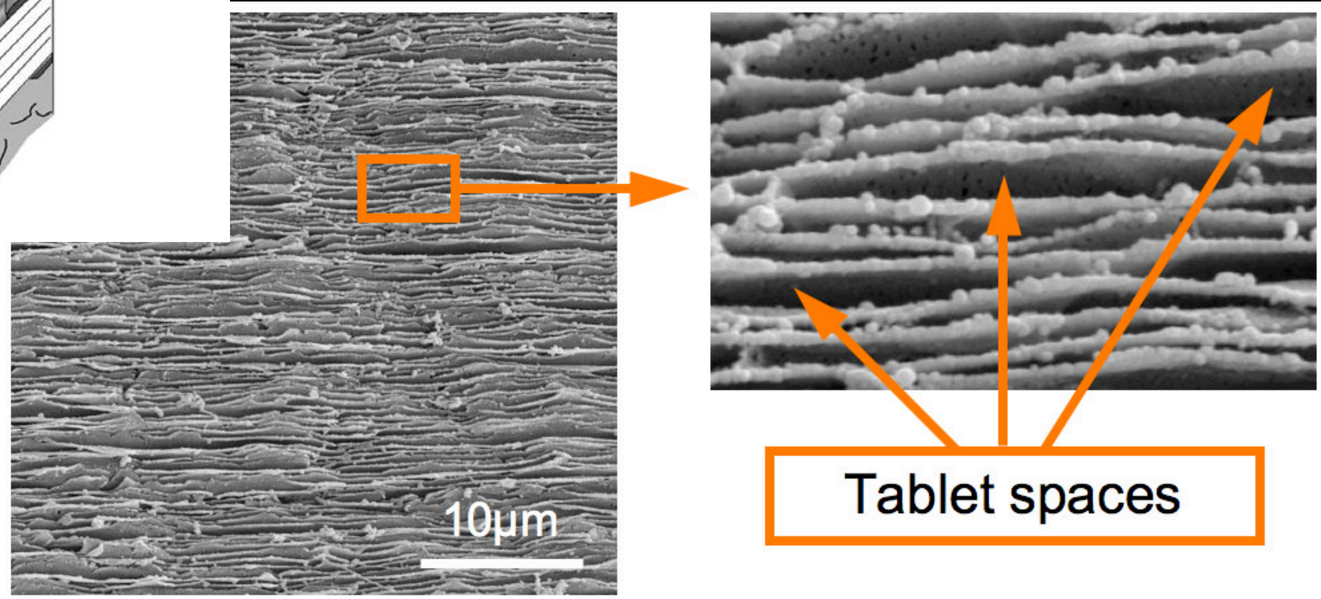
Biological Aragonite

Geological Aragonite

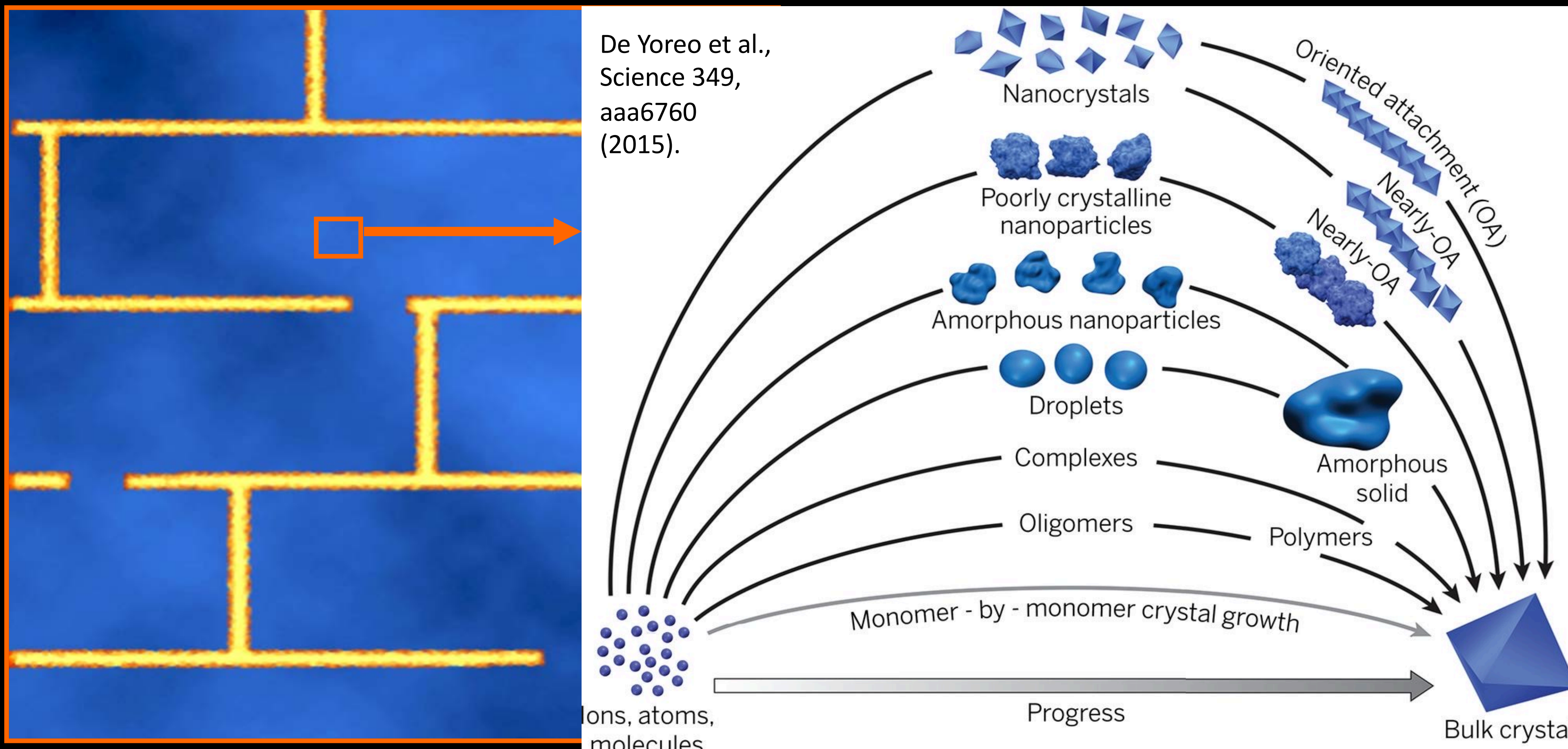
Interfacial control key in synthesis and assembly





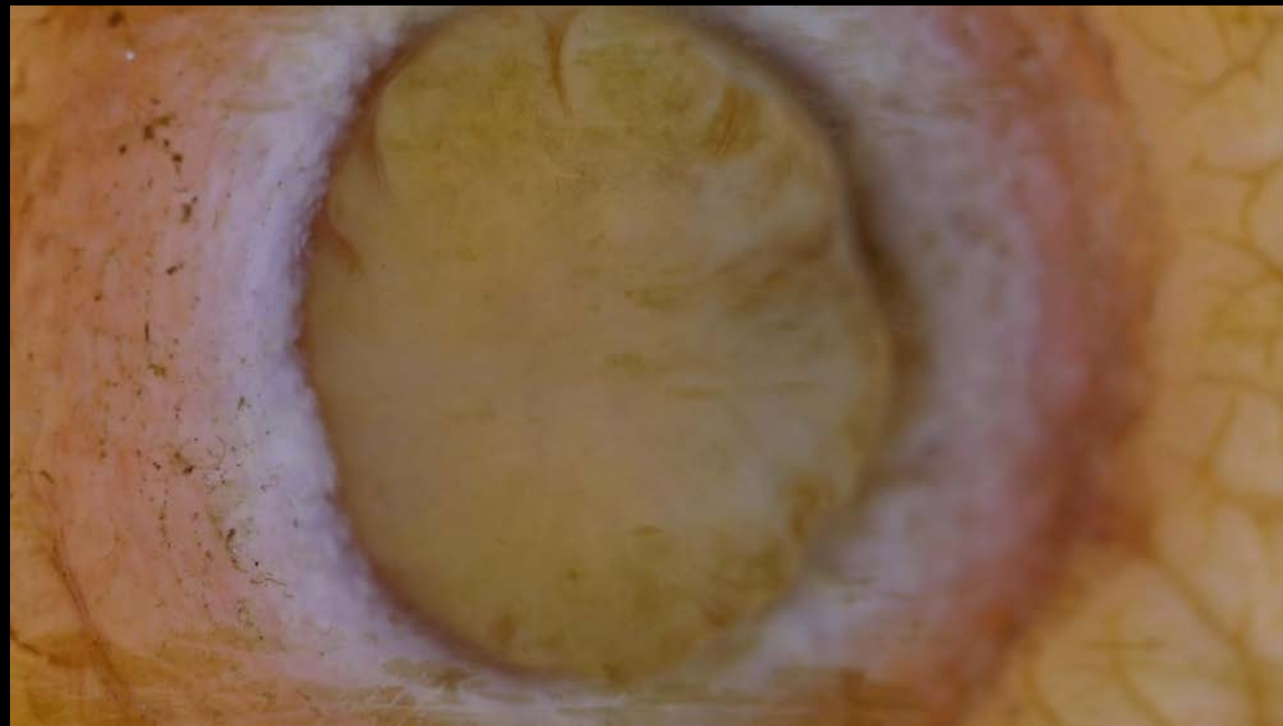


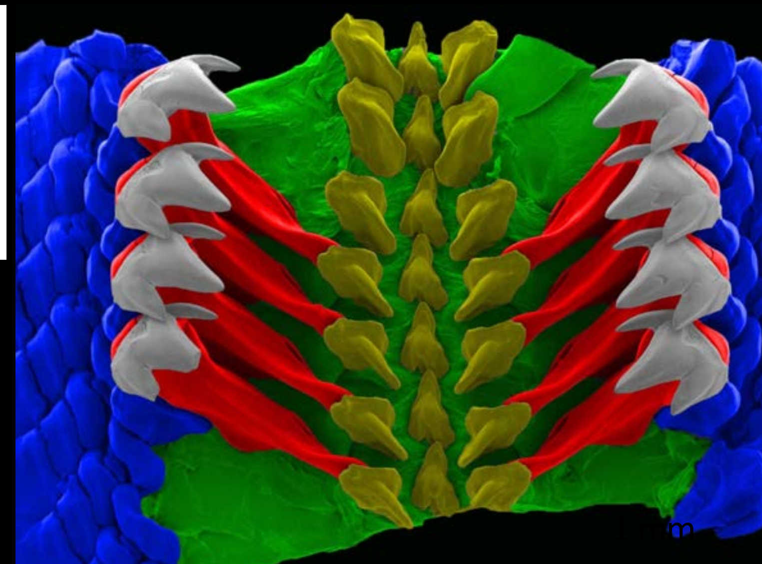
Controlled Nucleation and Growth of Biomaterials



- *Biology uses transient disordered (hydrated and amorphous) precursor phases – stabilized by organic → proteins*
- *Crystallization often occurs during dehydration with structural organic controlling crystallography (e.g., phase, orientation)*

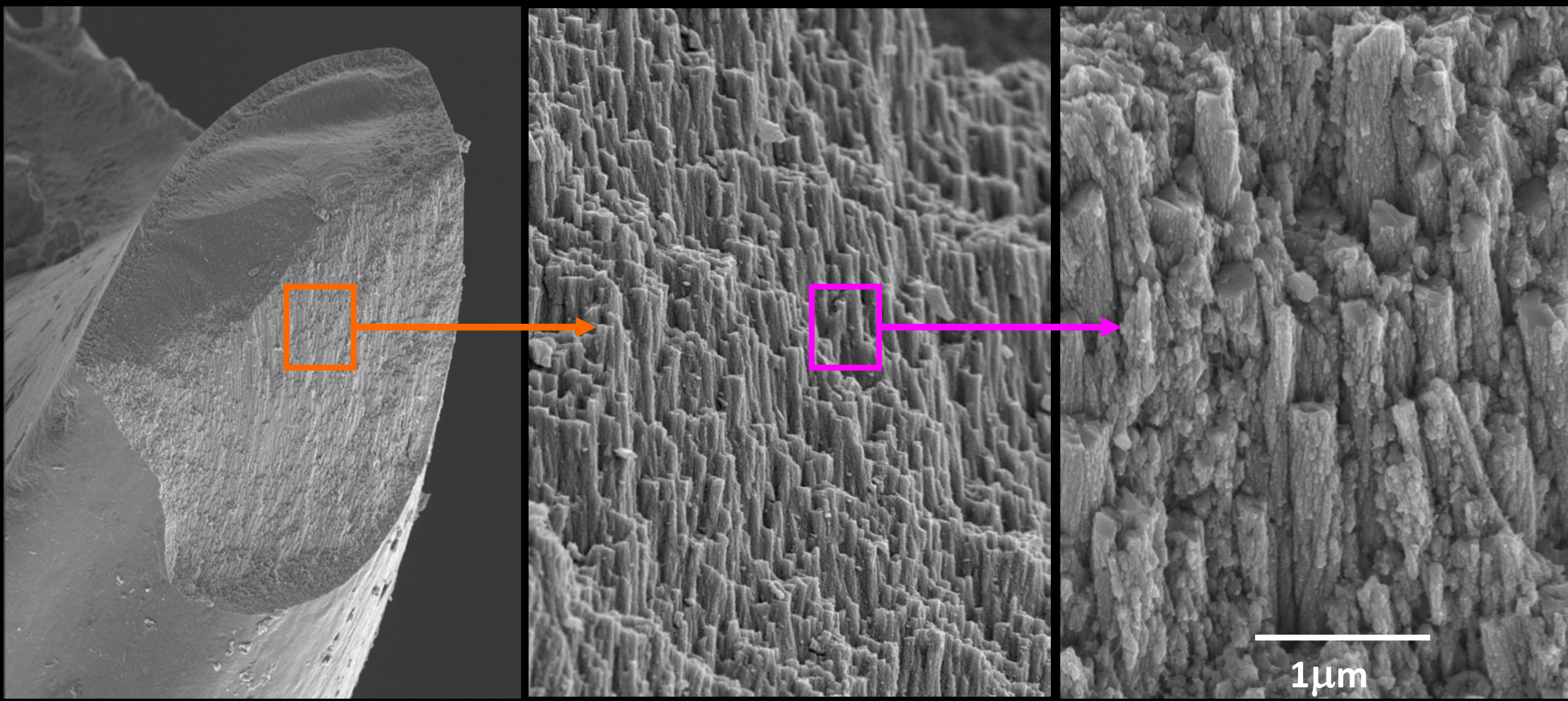
Flexible magnetic teeth from a mollusk?





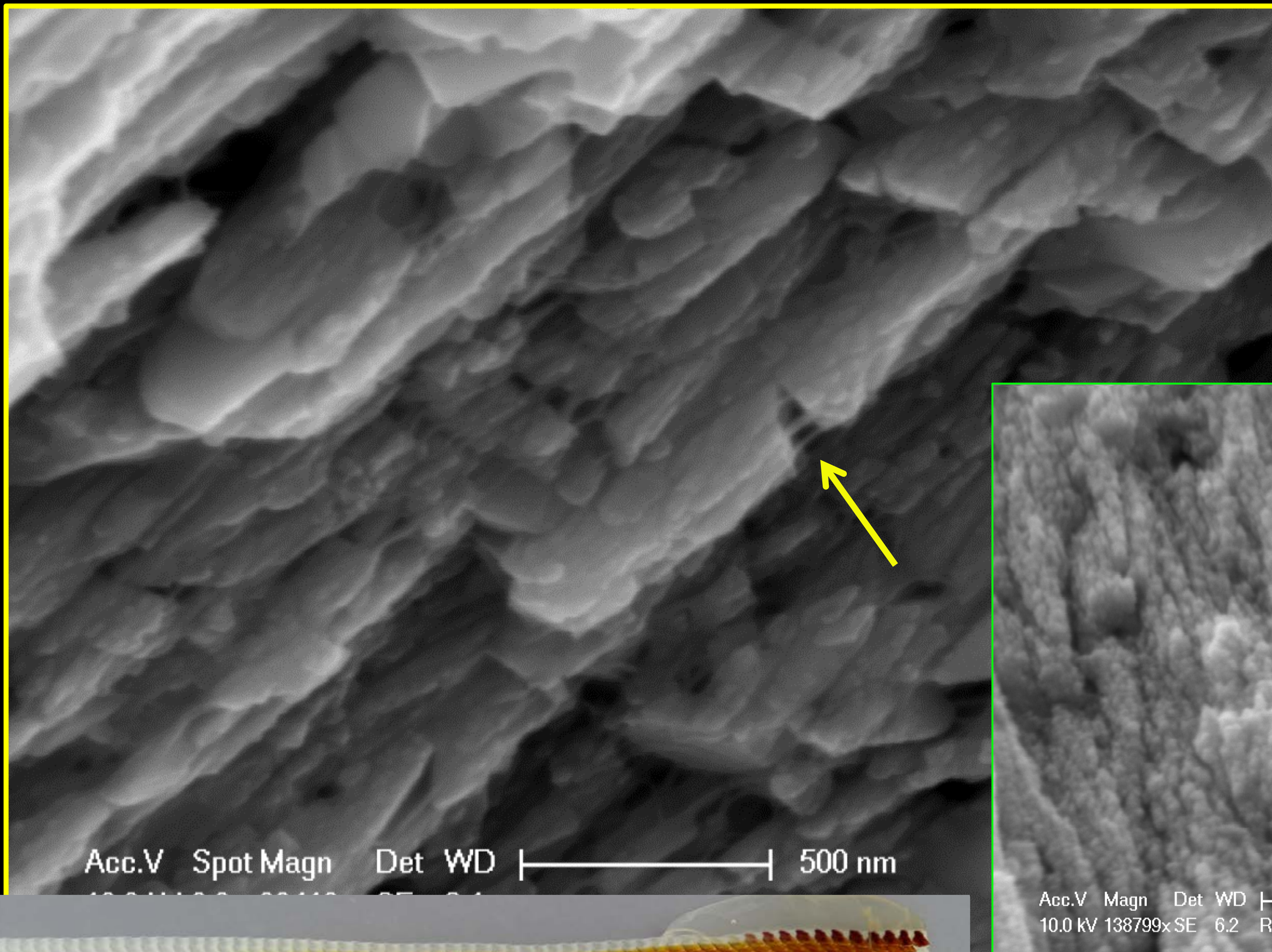
Lowenstam, H. A. (1962). GSA Bull. 73: 435-438; Lowenstam, H. A. (1974). In: The Sea E. D. Goldberg. New York, N.Y., John Wily & Sons: 715-796
Lowenstam HA, Weiner S. 1989. On Biomineralization. New York: Oxford Univ. Press. 324 pp

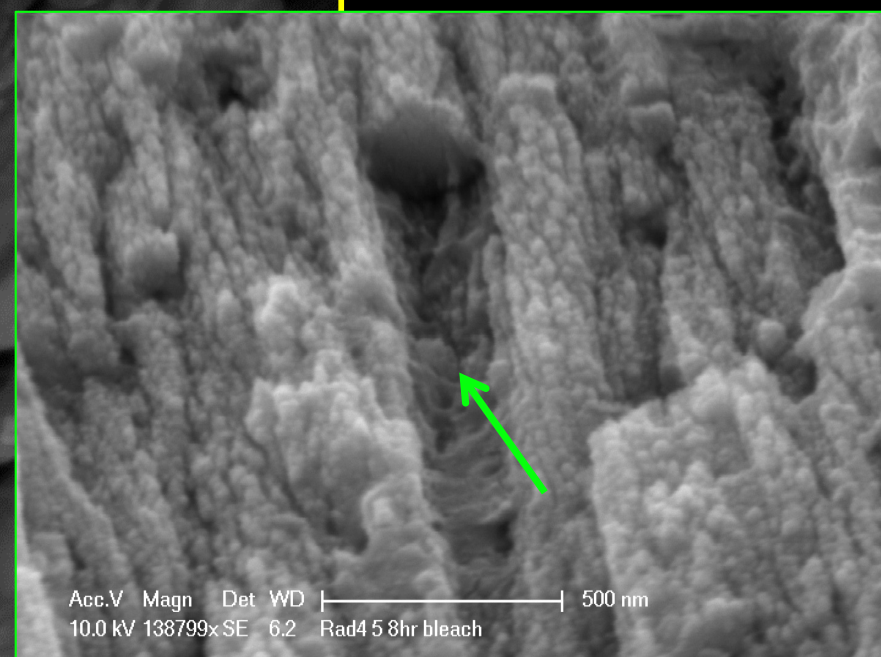
Hierarchical Design to Ultrahard Magnetic Teeth

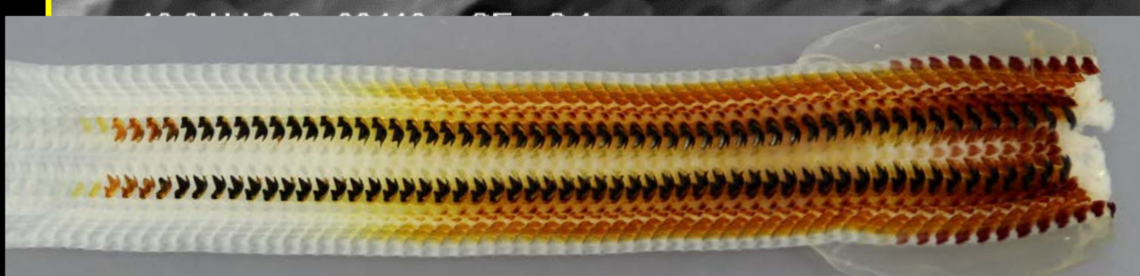


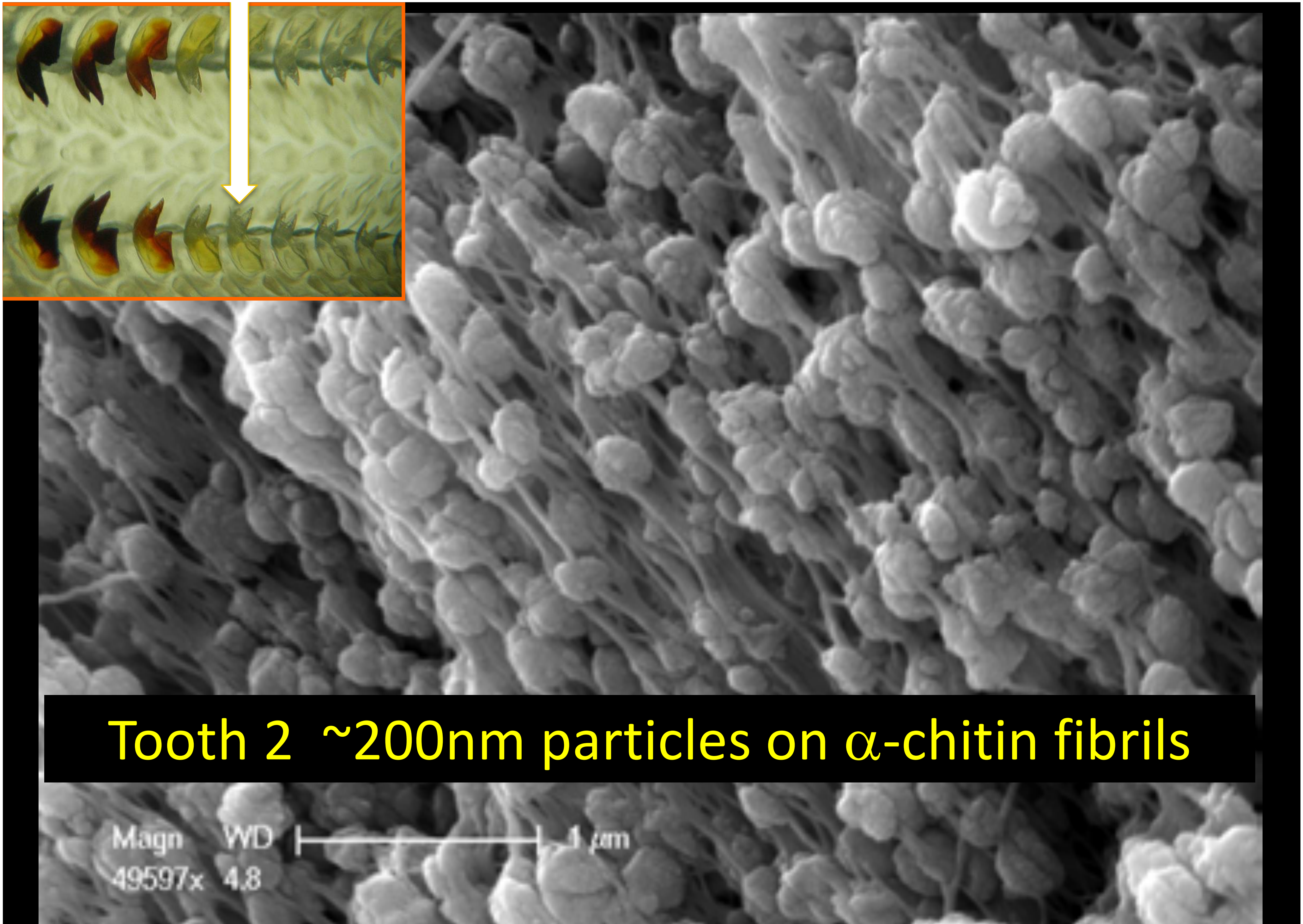
*Weaver et al., Materials Today, **13** (2010) 42-52.*
Grunenfelder et al. Adv. Funct. Mat., 24(39), (2014) 6093-6104.
de Obaldia et al. JMBBM, 48 (2015) 70-85.
de Obaldia et al., J. Mechanics and Physics of Solids, 96 (2016) 511-534.

Organic-Mineral Interfaces:
α-Chitin within and around rod…





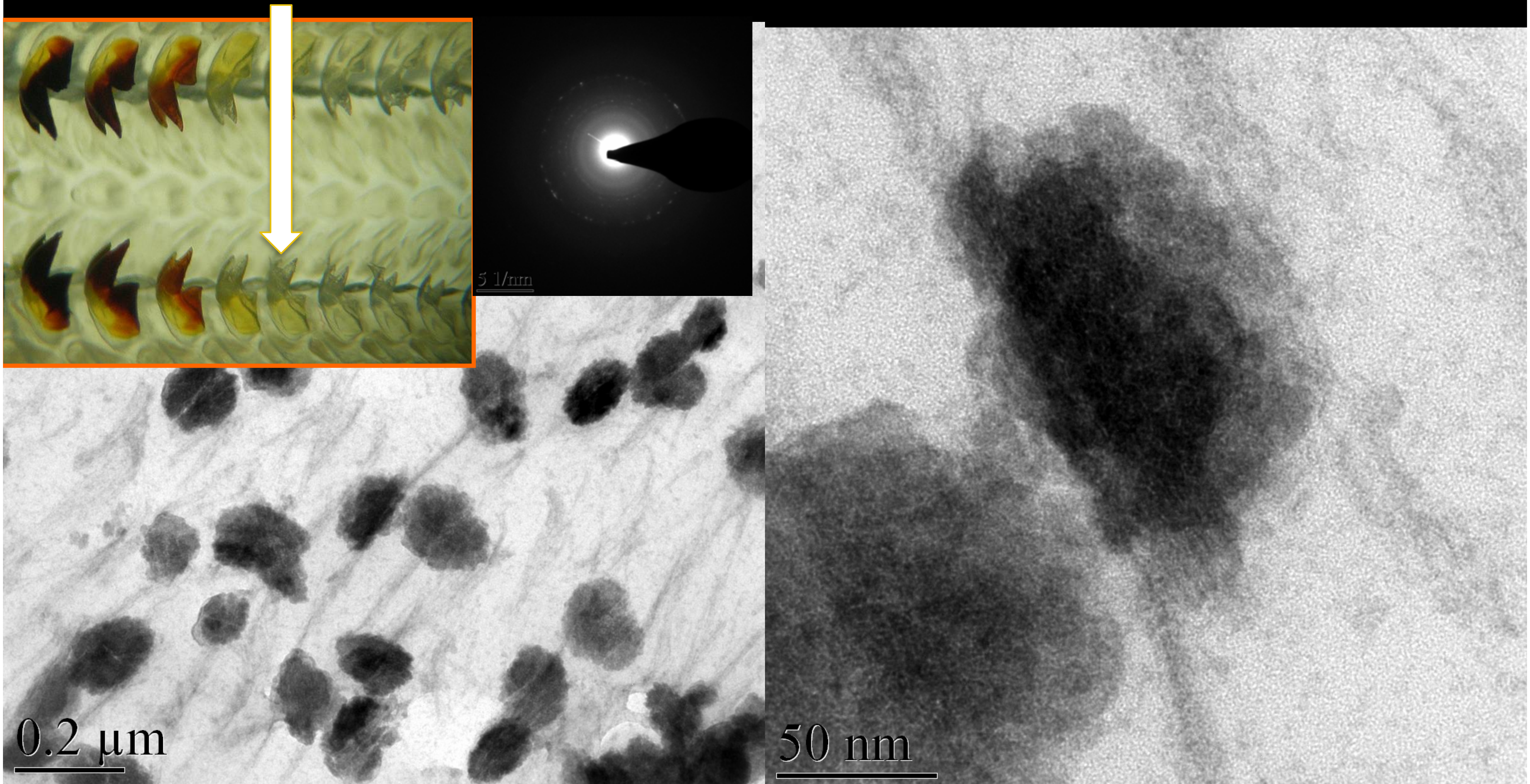




Tooth 2 ~200nm particles on α-chitin fibrils

Wang et al. *Adv. Funct. Mater.*, 23 (2013) 2908–2917.

Chitin-templated nucleation of iron oxide

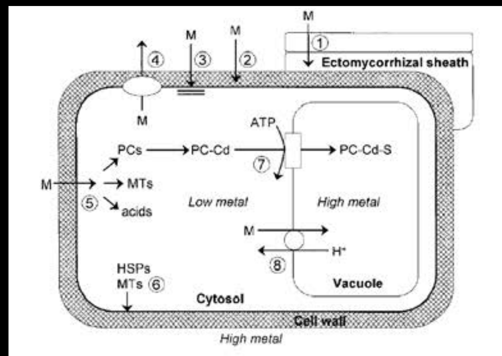


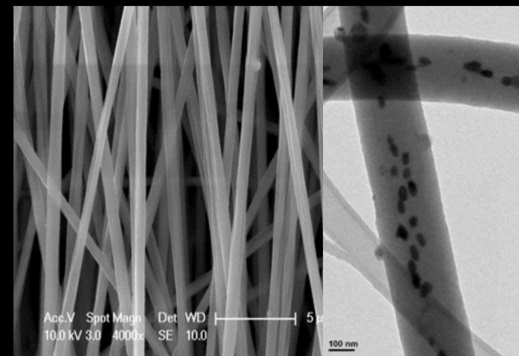
Ferrihydrite aggregated nanocrystals growing on α-chitin fibrils

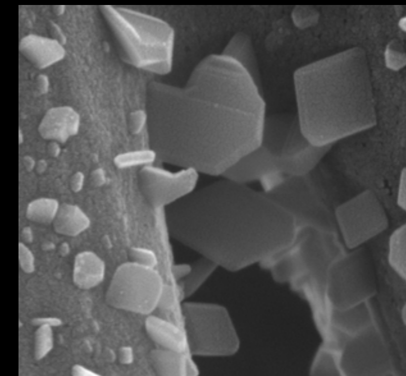
α-chitin + protein? templates iron oxide nucleation

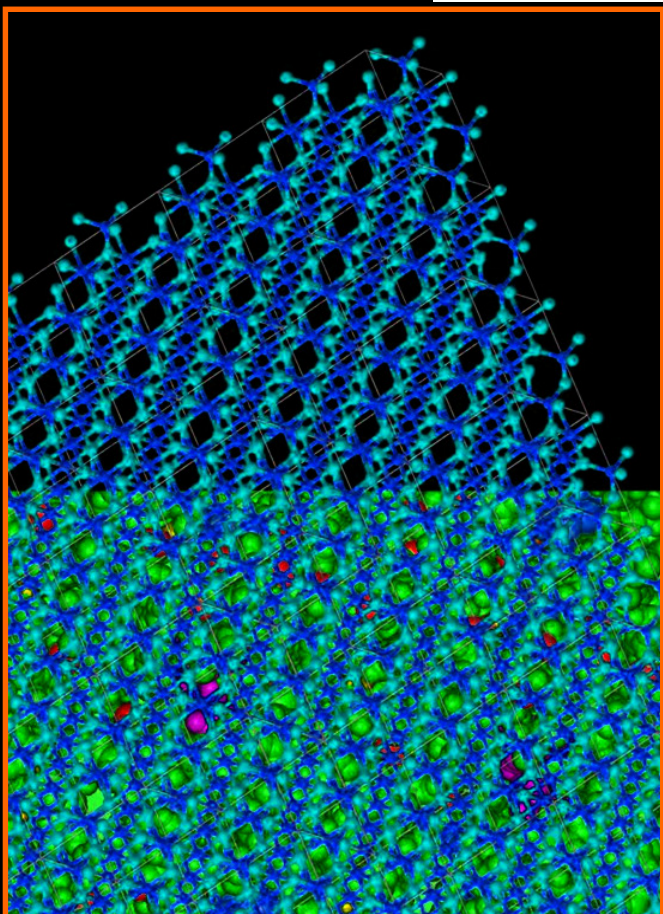
Wang et al. *Adv. Funct. Mater.*, 23 (2013) 2908–2917.

Translating Biology to Nanotechnology at UCI

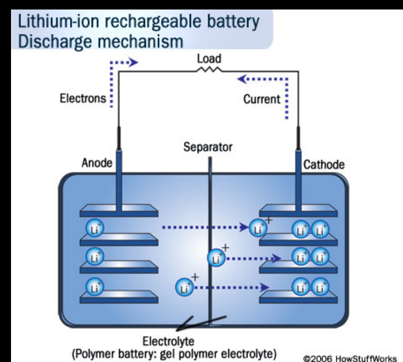


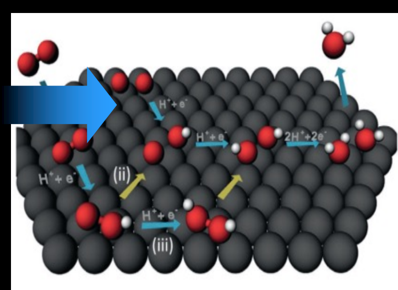


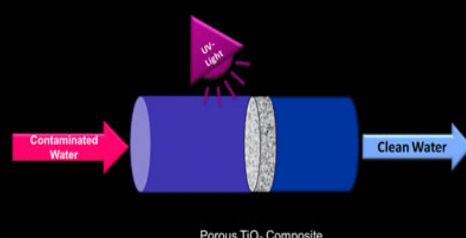




Structure-Directing Organic Scaffolds



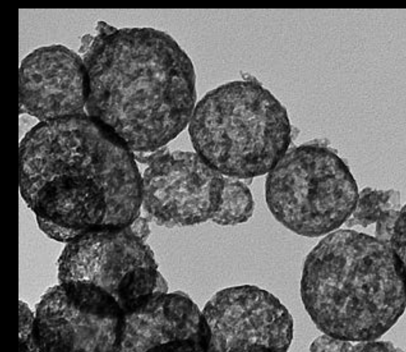




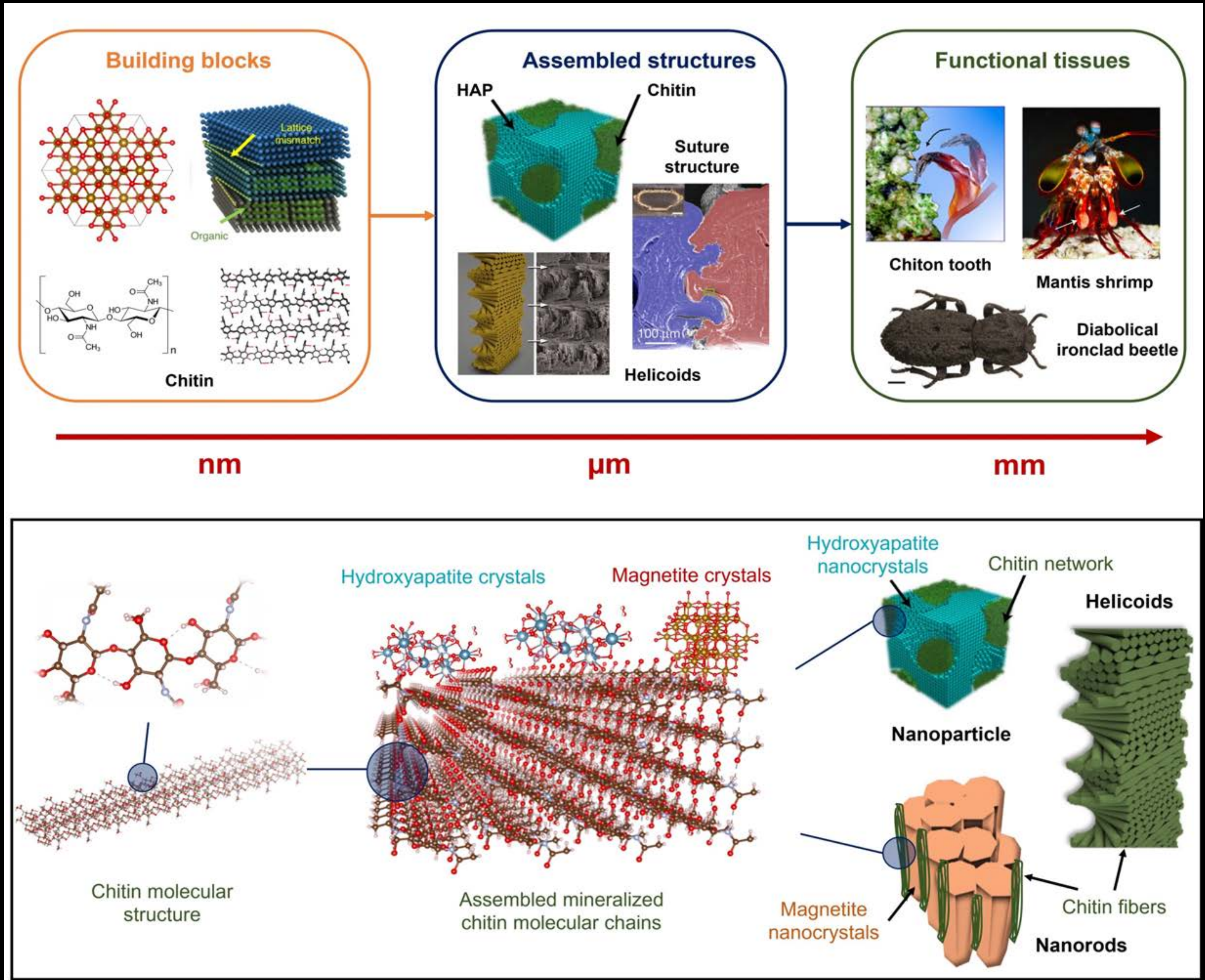
Fast Charging / Long Lasting Batteries

Fuel Cells that are 1/160 the cost!

Water Purifying Filters

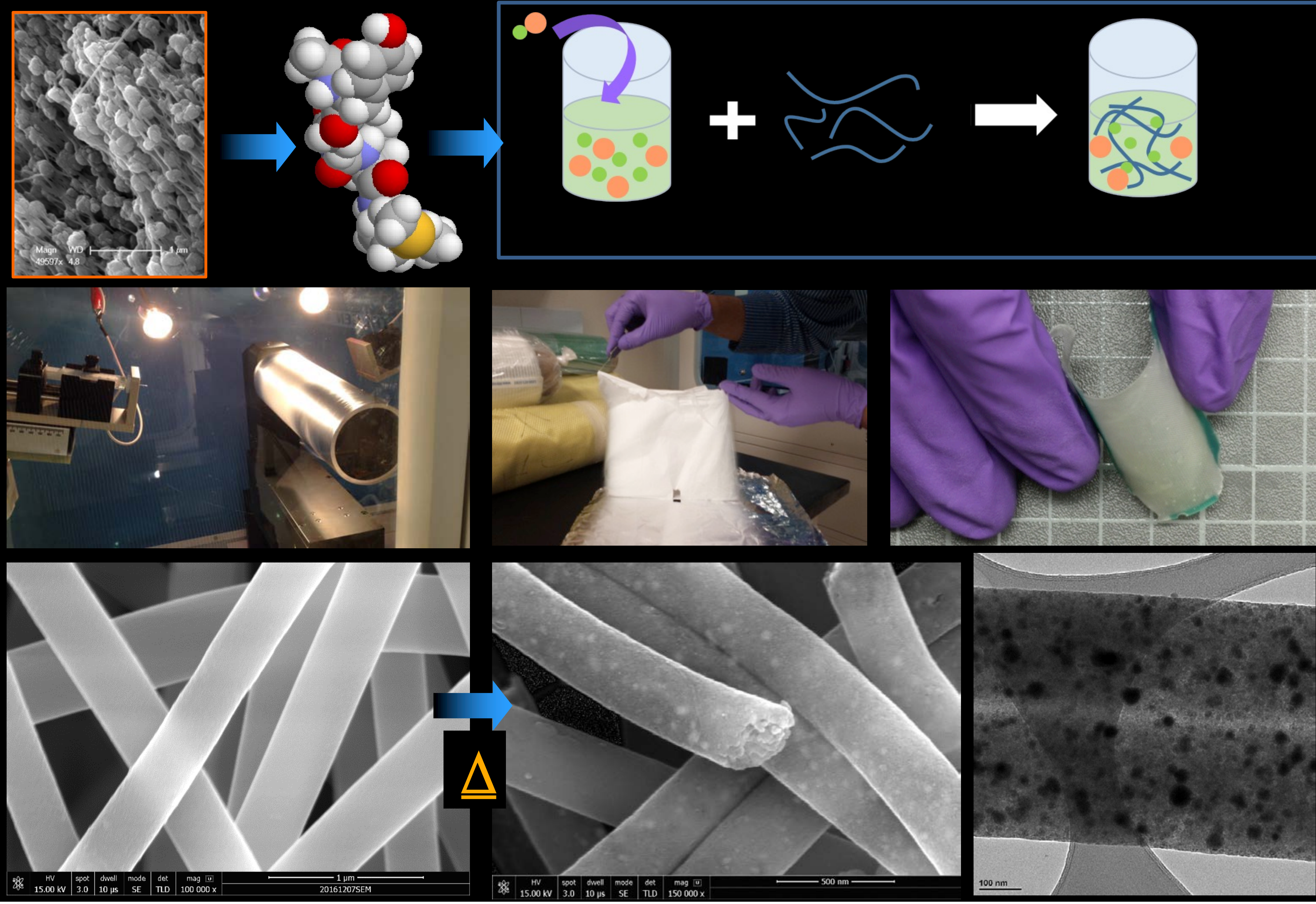


Common architectures based on scaffolding

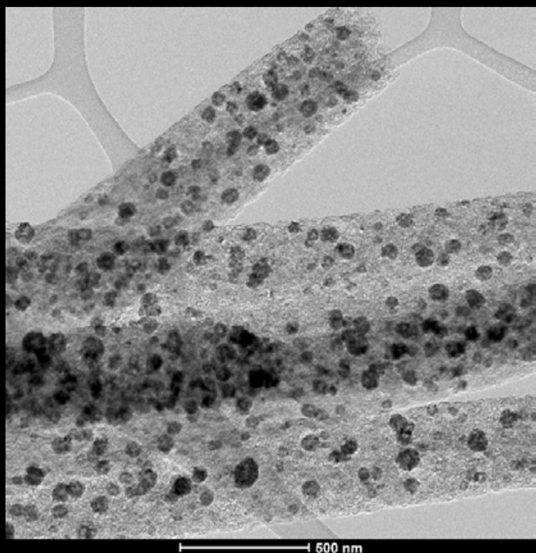


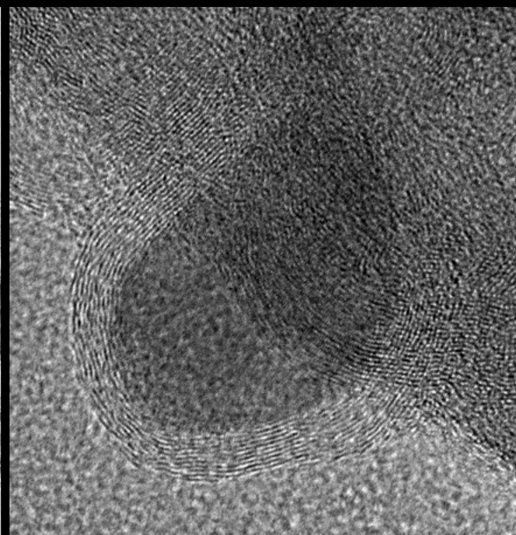
Huang, Kisailus et al., *Acc. Chem. Res.* (2022), 55, 10, 1360–1371.

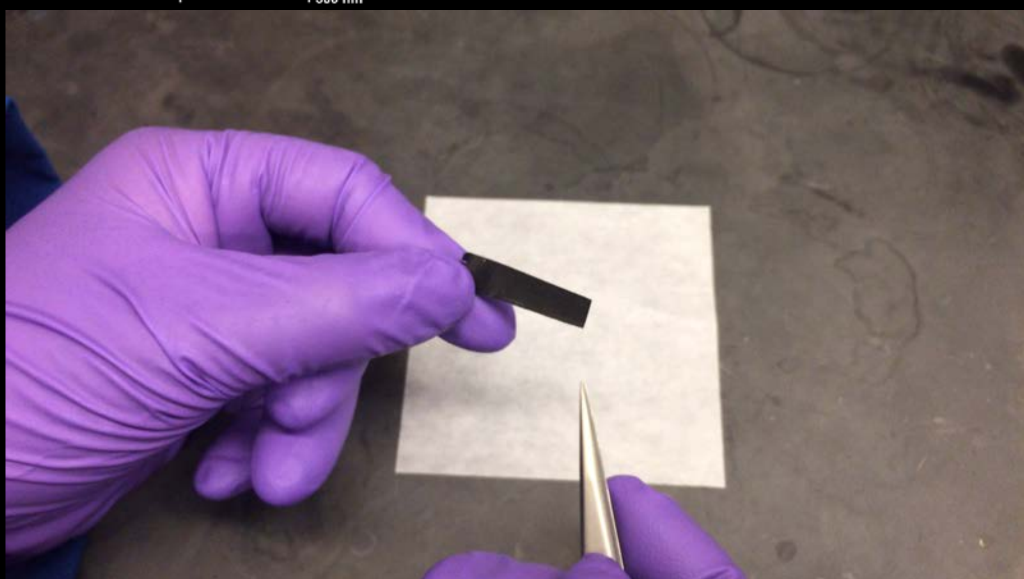
Synthesizing polymer-biopolymer-metal hybrids: Towards non-Biogenic Materials

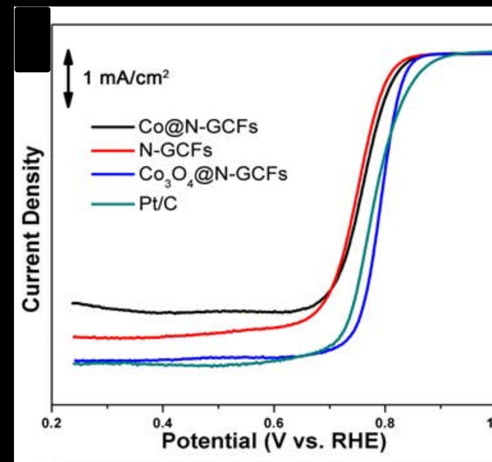


Functional Organics Drive Controlled Synthesis of M/MO/MN Nanofibers within Graphitic Networks

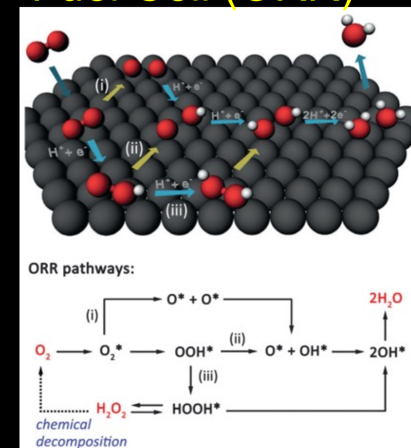


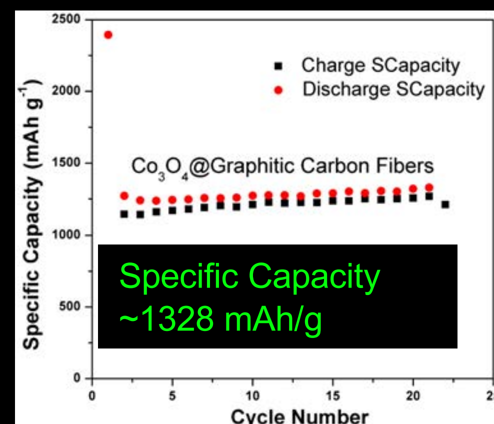




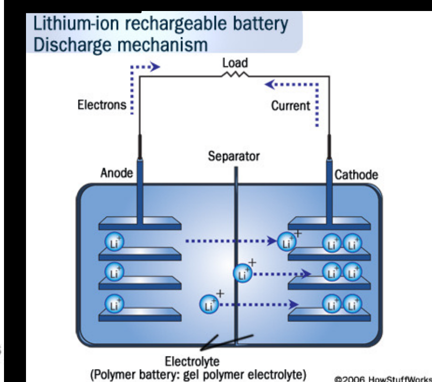


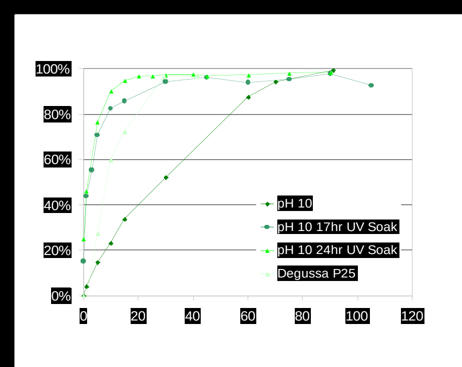
Fuel Cell (ORR)



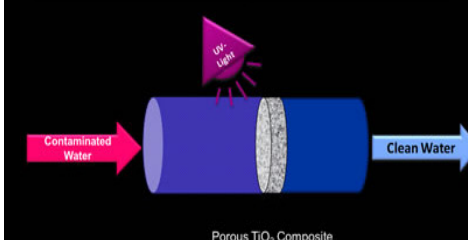


LIBs



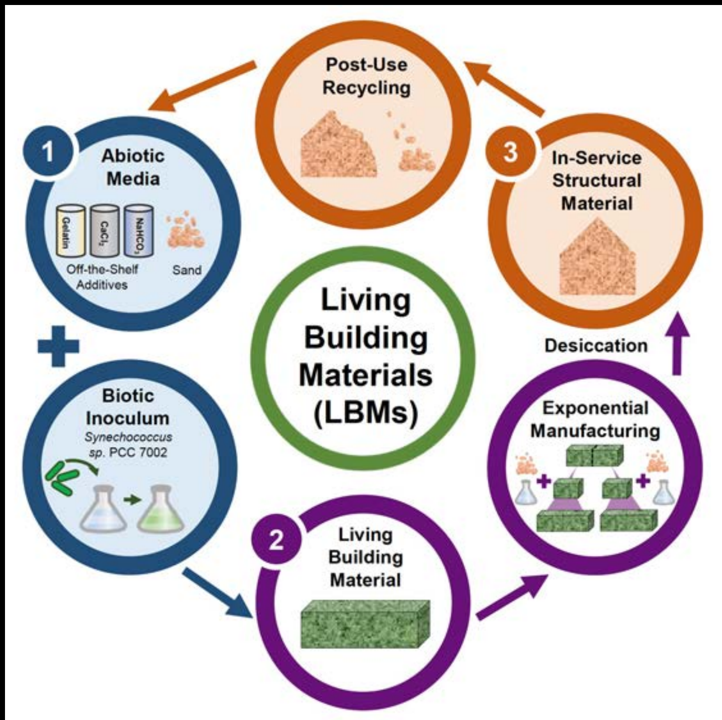


Photocatalytic Filters

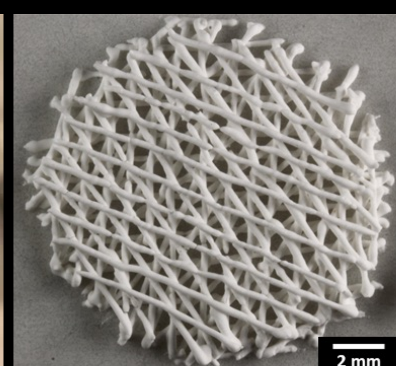


H. Tang, D. Kisailus, et al. *Small*, 14 (2018), 1703459.

Potential for Scalable Manufacturing of Autonomous Structures



- Utilization of microbes to build and reuse structures
- To date: Limited set of microbes and minerals (e.g., $CaCO_3$)
- Potential for structures to be built in extreme environments with a *broader base of material systems*

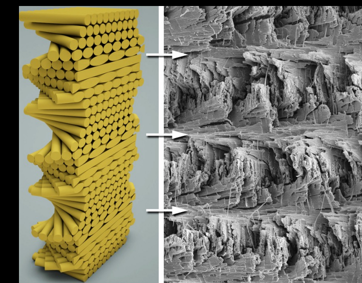


Tuning ink and writing conditions for multi-functional structures

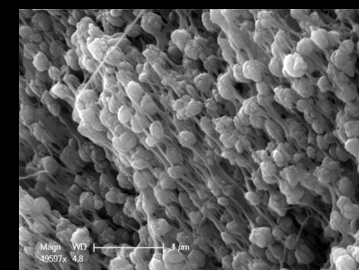
https://doi.org/10.1016/j.matt.2019.11.016

Summary

Biology provides 100's MYA of experiments to synthesize nanostructures for optimized function under extreme conditions – convergent designs revealed.

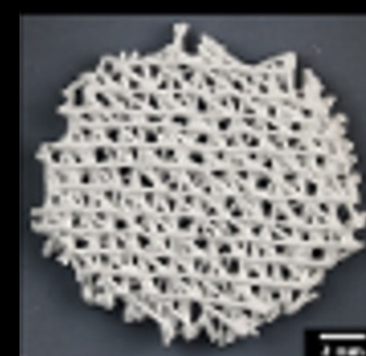


Biology utilizes organics to not only precisely control the storage, transport, nucleation, growth and transformation of nanomaterials, but provides function



Integration of biopolymer scaffolding plus bio-functionality guiding inorganic synthesis → multifunctional materials

Translation towards Scalable Synthesis of Multifunctional Architected Materials



Acknowledgements

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Yuka Narahara   Ezra Sarmiento   Andrew Nguyen

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Collaborators

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Jocelyne DiRuggiero (JHU)   Dula Parkinson (LBL)   Richard Wuhrer (UWS)

Luis Zepeda Ruiz (LLNL)   Michiko Nemoto (Okayama)   Guillaume Freychet (BNL)

Organisms

Odontodactylus scyllarus, Cryptochiton stelleri,
Phloeodes diabolicus

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AFOSR, AFRL, ARO

Thank you !!!

Questions???