Chemical Design of Functional Protein-Based Assemblies and Materials

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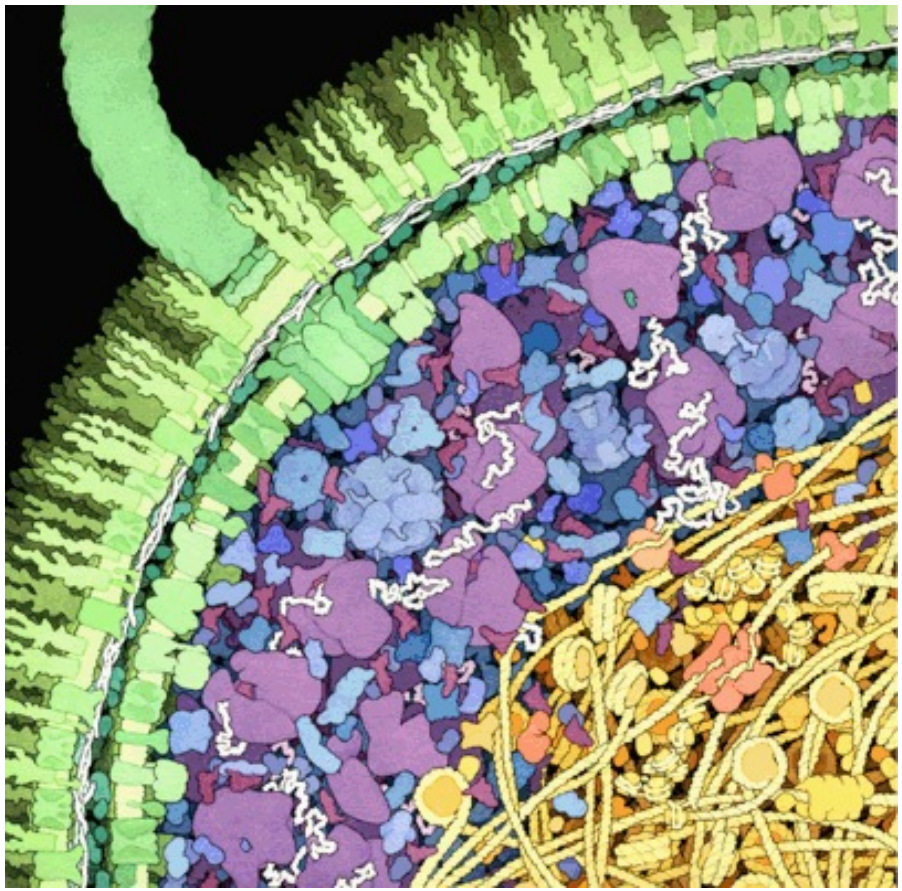
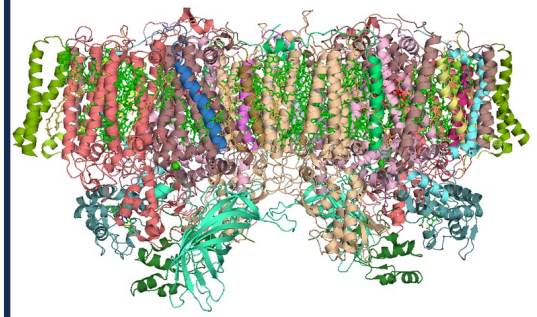
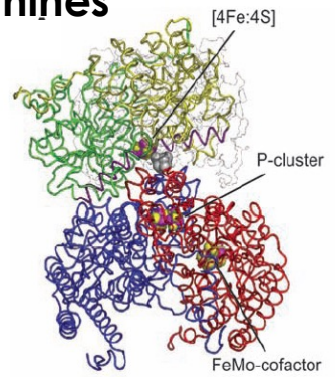
Life's complexity is largely driven by supramolecular protein assemblies



Biological machines

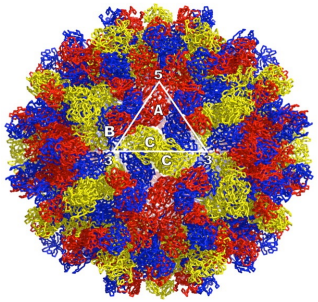


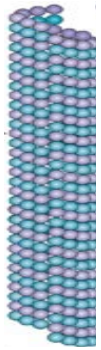
photosystem II

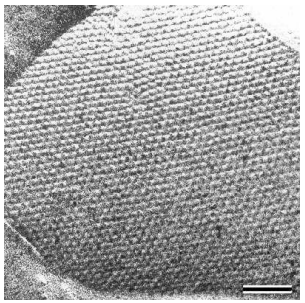


nitrogenase

Biological materials

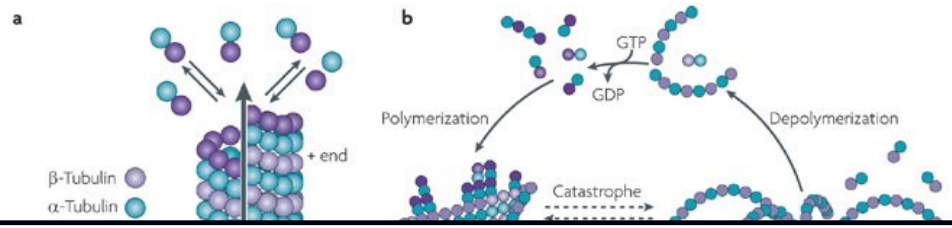






polyhedral containers, cytoskeletal assemblies, surface layers, etc.

Crystalline, yet responsive and flexible

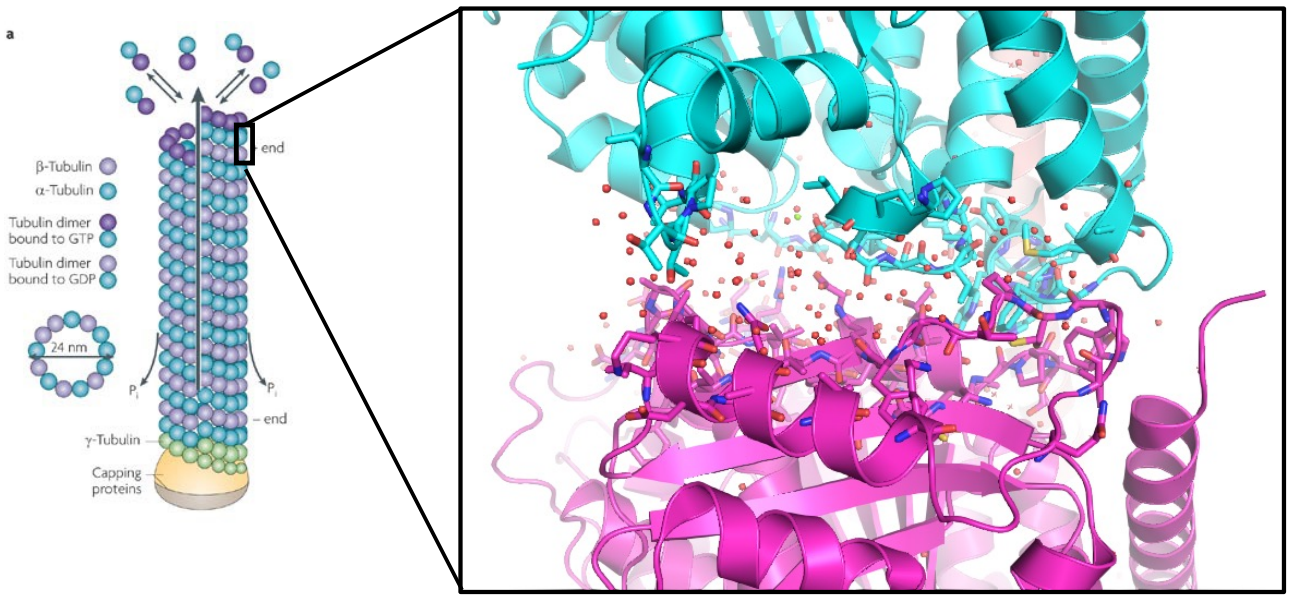


Question: Can we design artificial protein assemblies that combine the structural coherence of crystalline materials with the responsive and adaptive behavior of biological/polymeric systems?

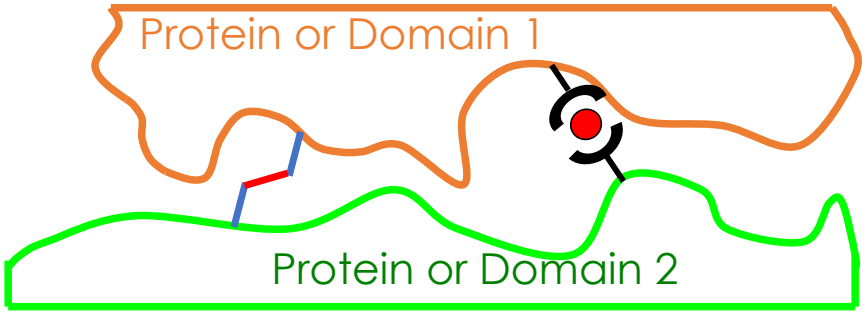
→ A better understanding of natural design principles of adaptive biomolecular materials

→ New structures and properties unencumbered by cellular/evolutionary constraints

Natural protein-protein interfaces are highly complex

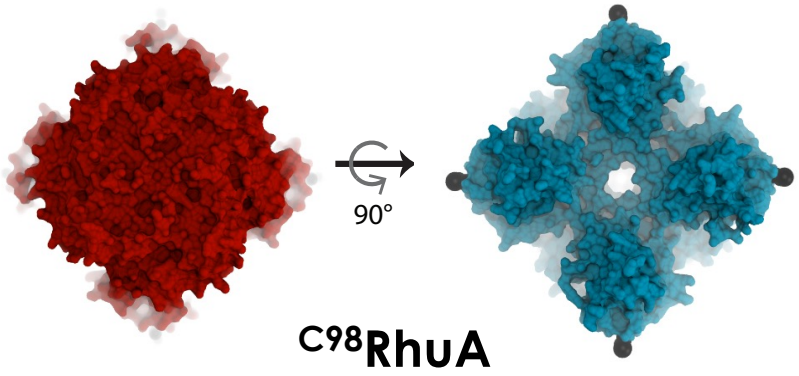


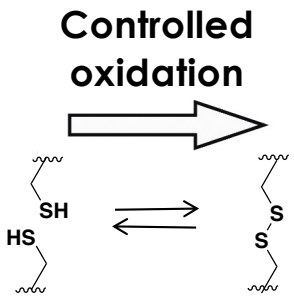
Chemically controlled protein-protein interactions



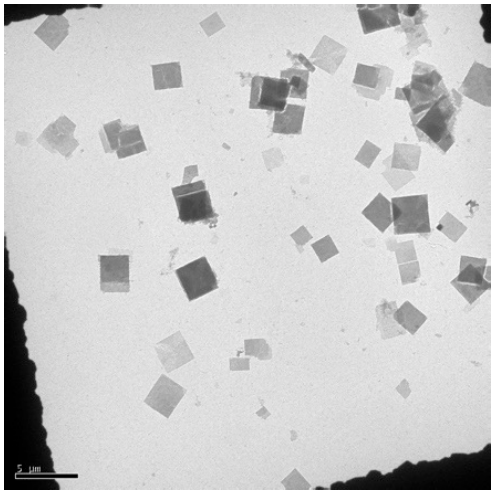
- strength + directionality
- reversibility + inherent chemical control
- flexibility (due to nature of bonds and small footprint).

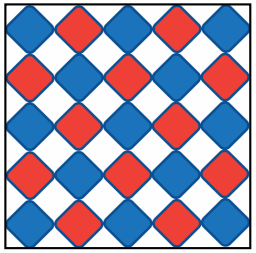
Disulfide-directed 2D protein assemblies

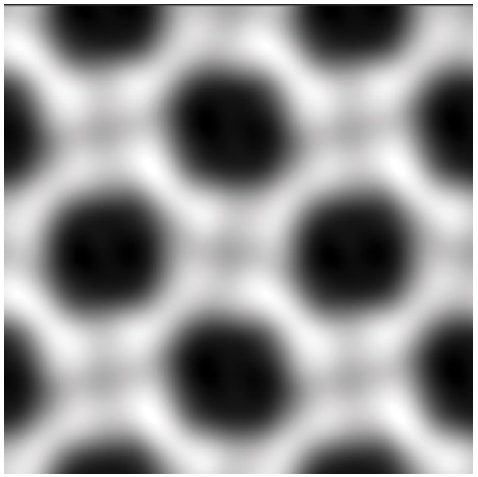


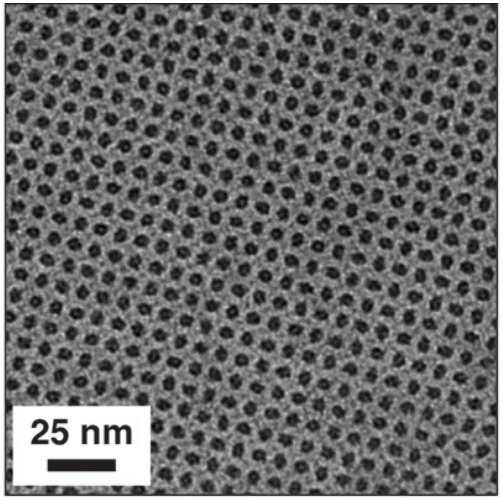


E = -100 to -350 mV



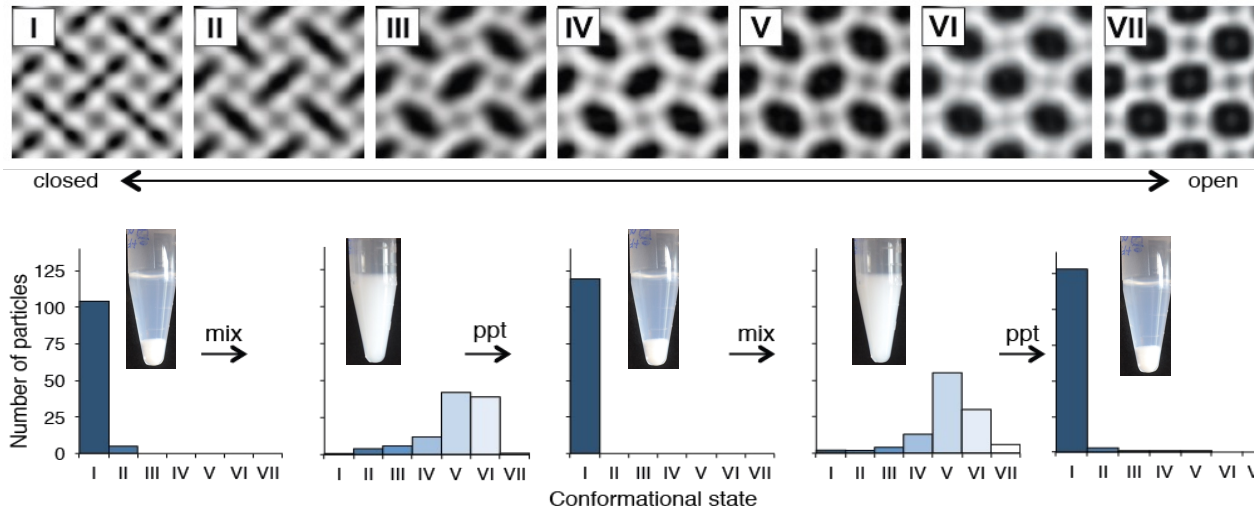


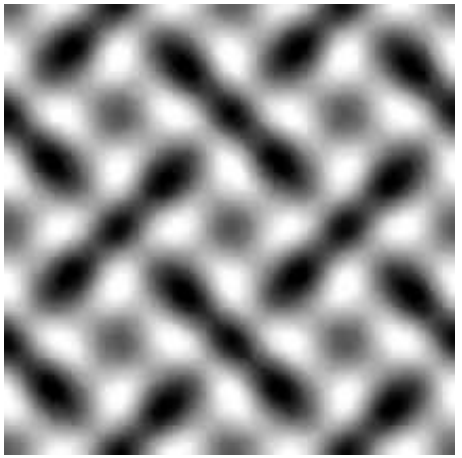




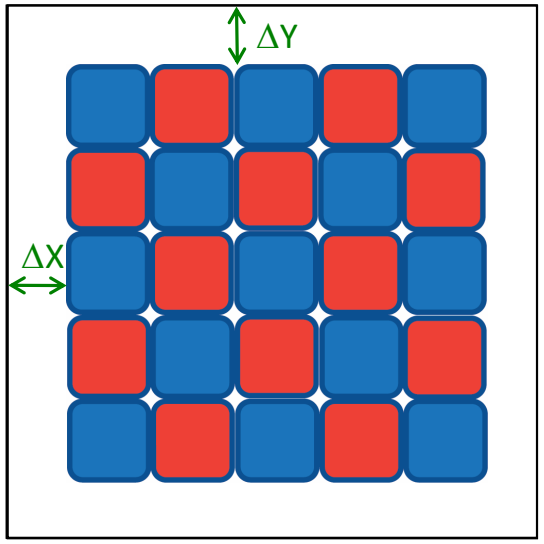
Suzuki, Nature, **533**, 369 (2016)

Coherent dynamics of 2D RhuA crystals





Suzuki, Nature, **533**, 369 (2016)
Alberstein, *Nat. Chem.* 10, 732 (2018)

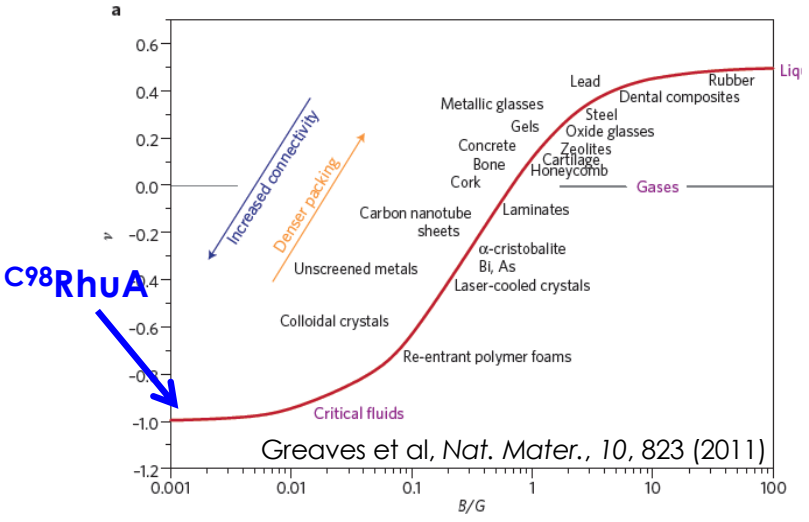


Poisson's ratio:

$\nu = -\Delta x/\Delta y$

$(-1 < \nu < 0.5)$

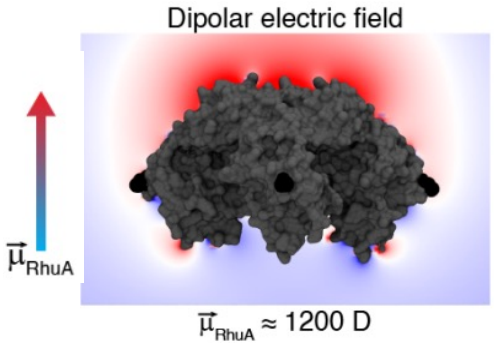
$\nu_{RhuA} = -1$

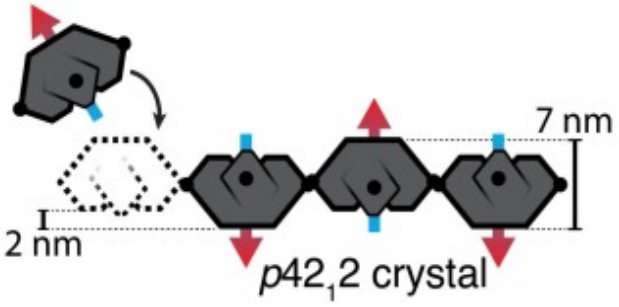


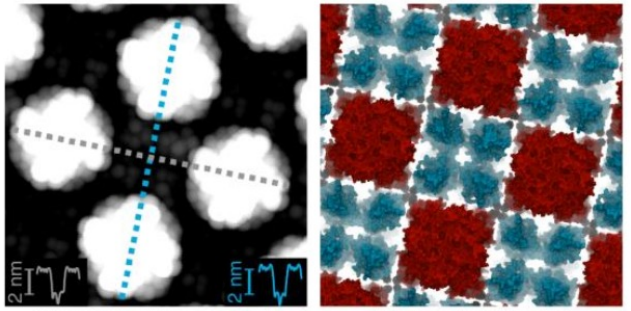
Greaves et al, *Nat. Mater.*, *10*, 823 (2011)

Controlling the in-plane patterning of RhuA molecules

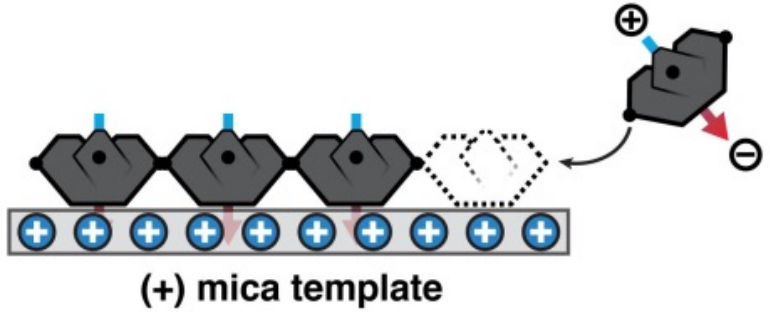
In bulk solution:

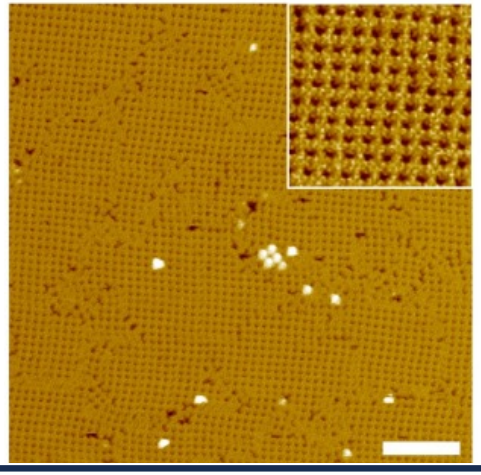






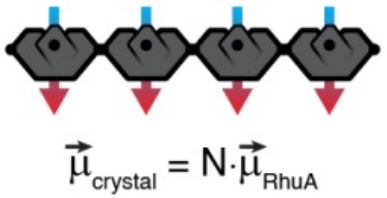
On solid substrates:

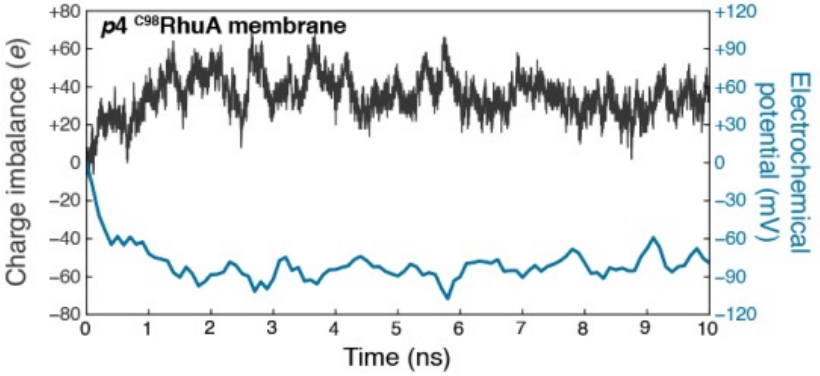


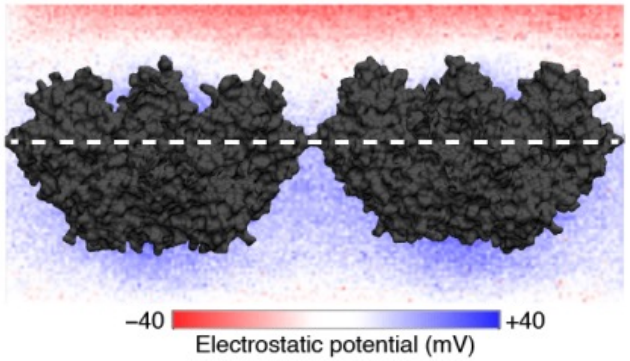


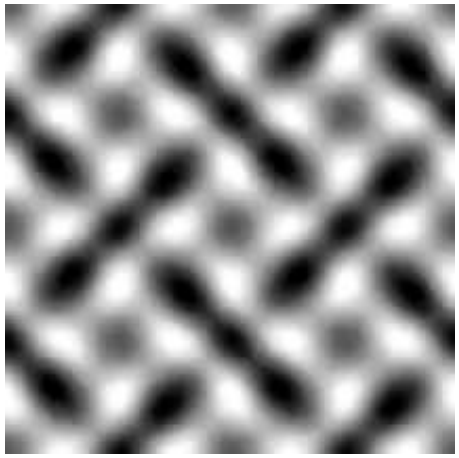
Zhang, *Nat. Commun*, **11,** 3770 (2020)

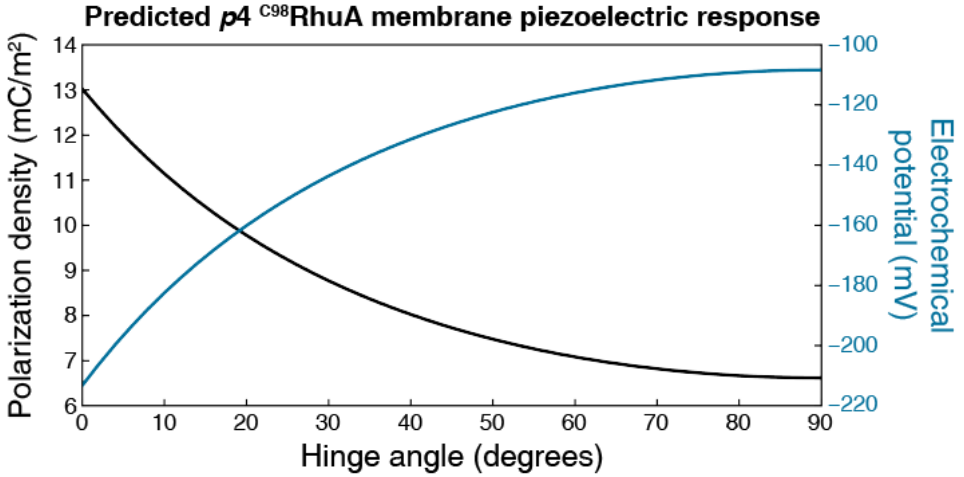
Predicted piezoelectric properties of templated RhuA crystals





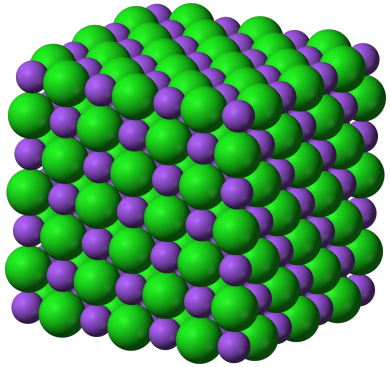






Zhang, Nat. Commun, **11,** 3770 (2020)

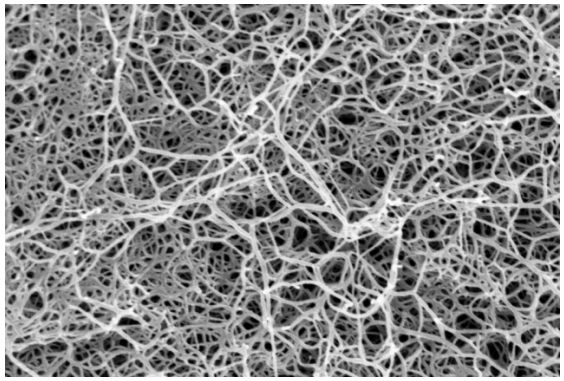
Pushing dynamism of crystalline materials into 3D



Crystalline materials:

- High Structural Order and Strength
- Low Flexibility/Responsiveness

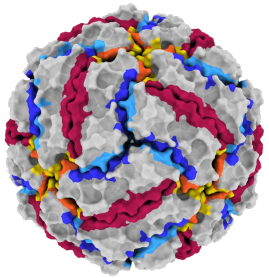
+



Soft, polymeric materials:

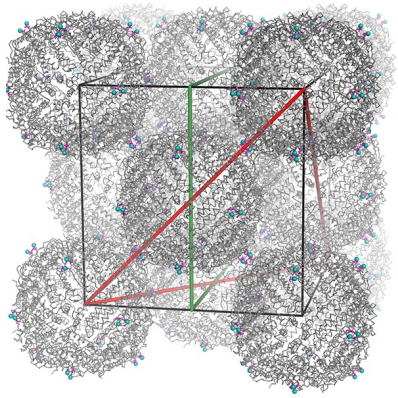
- High flexibility and adaptiveness
- Low structural order/coherence/ strength

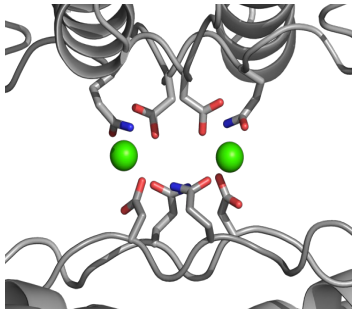
Polymer-Integrated Protein Crystals (PIX)

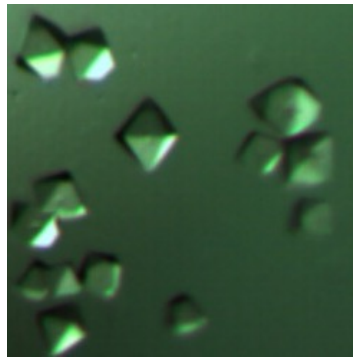


Ferritin
(432 symmetry)

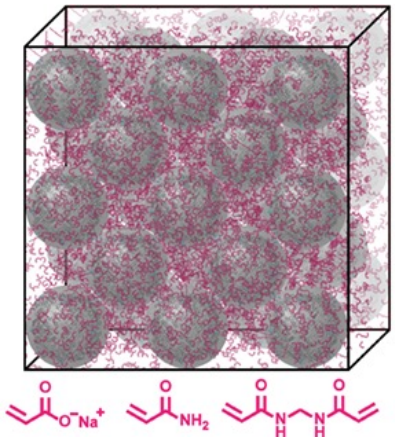
+Q84/E86
+ Ca^{2+}





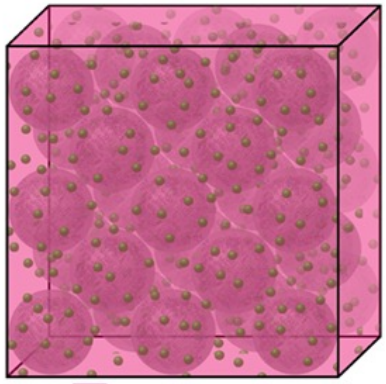


fcc crystals (~2 GPa)

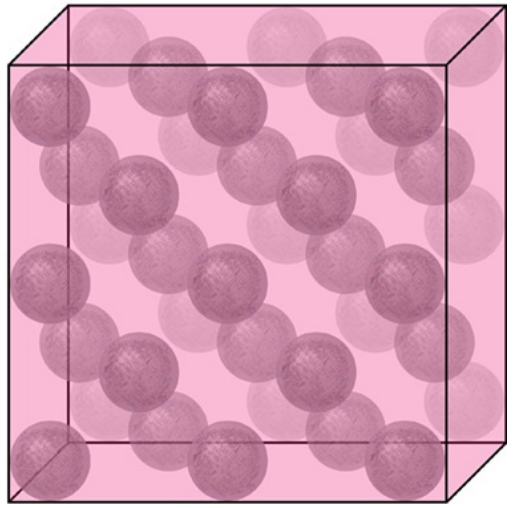


Acrylate/acrylamide

+ APS/
TEMED
+ NaCl

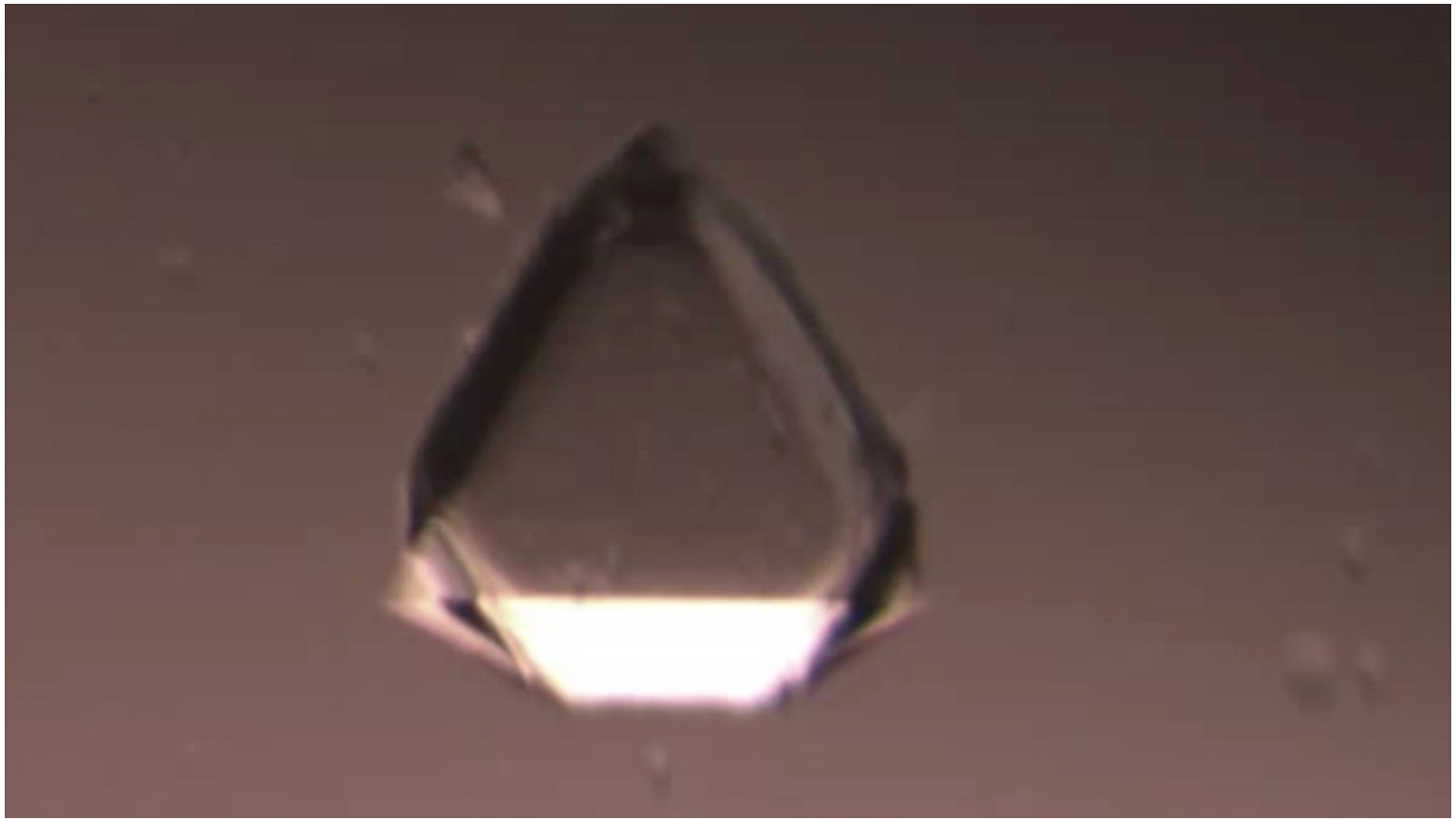


+ H_2O
– M^{2+}
+ NaCl
+ M^{2+}



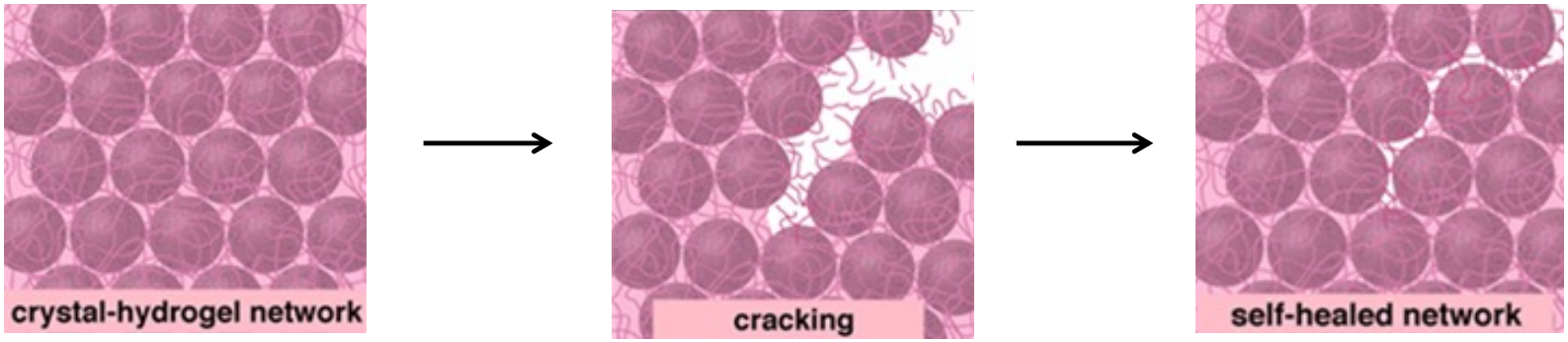
Zhang *et al.*, *Nature*, 557, 86 (2018)

Reversible expansion and contraction of PIX

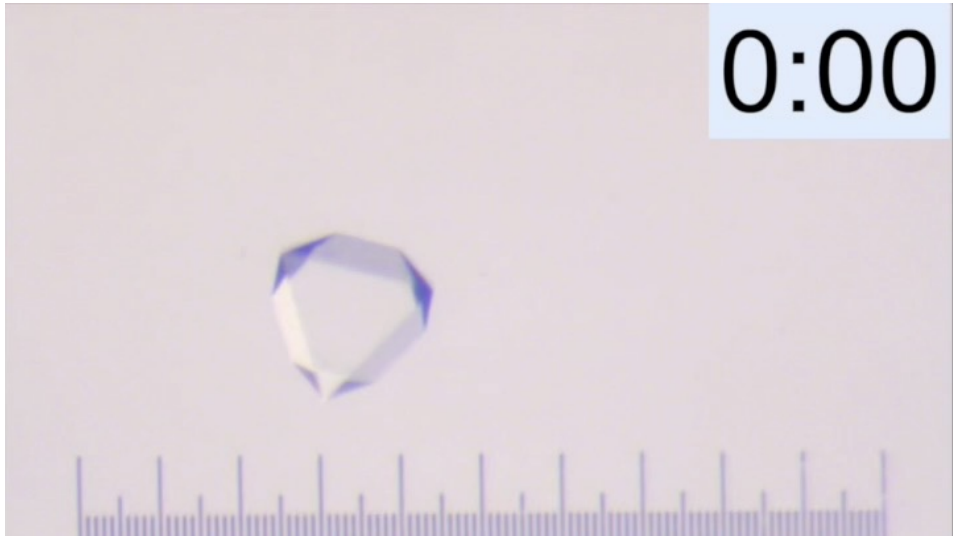


Zhang *et al.*, *Nature*, 557, 86 (2018)

Self-healing properties of PIX

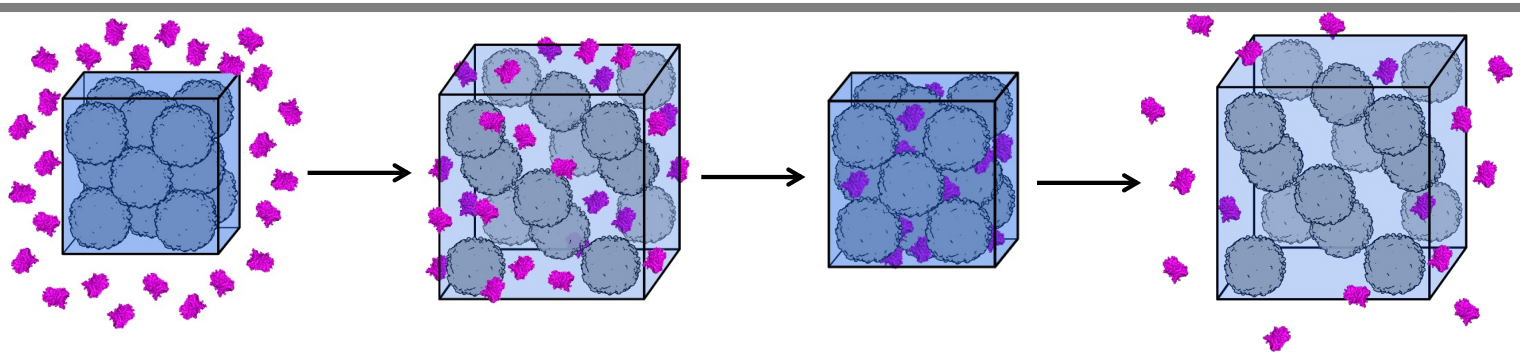


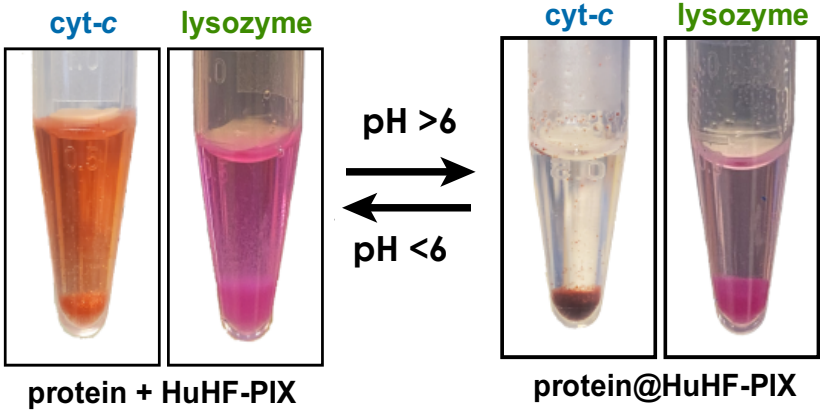
self-healing enabled by loose polymer chains previously associated with protein surfaces

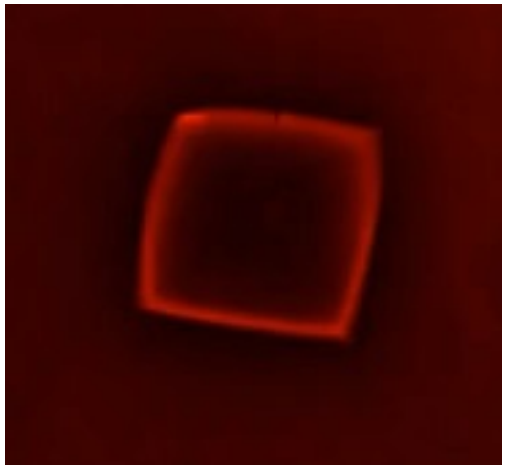


Zhang *et al.*, *Nature*, 557, 86 (2018)

Controlled protein encapsulation/release by PIX



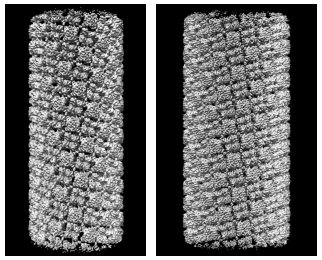




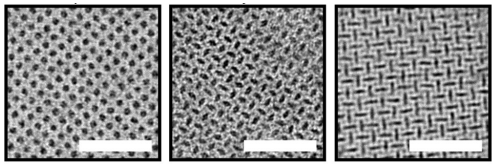
Han, Na, et al., *J. Am. Chem. Soc.*, 144, 10139 (2022)

Han et al., *J. Am. Chem. Soc.* 145, 19932 (2023)

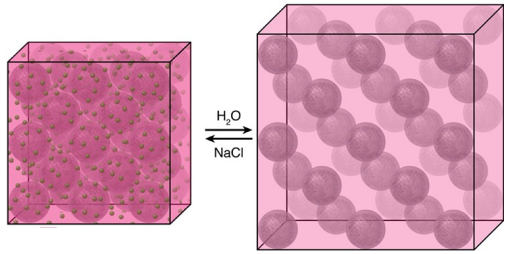
SUMMARY



1D



2D



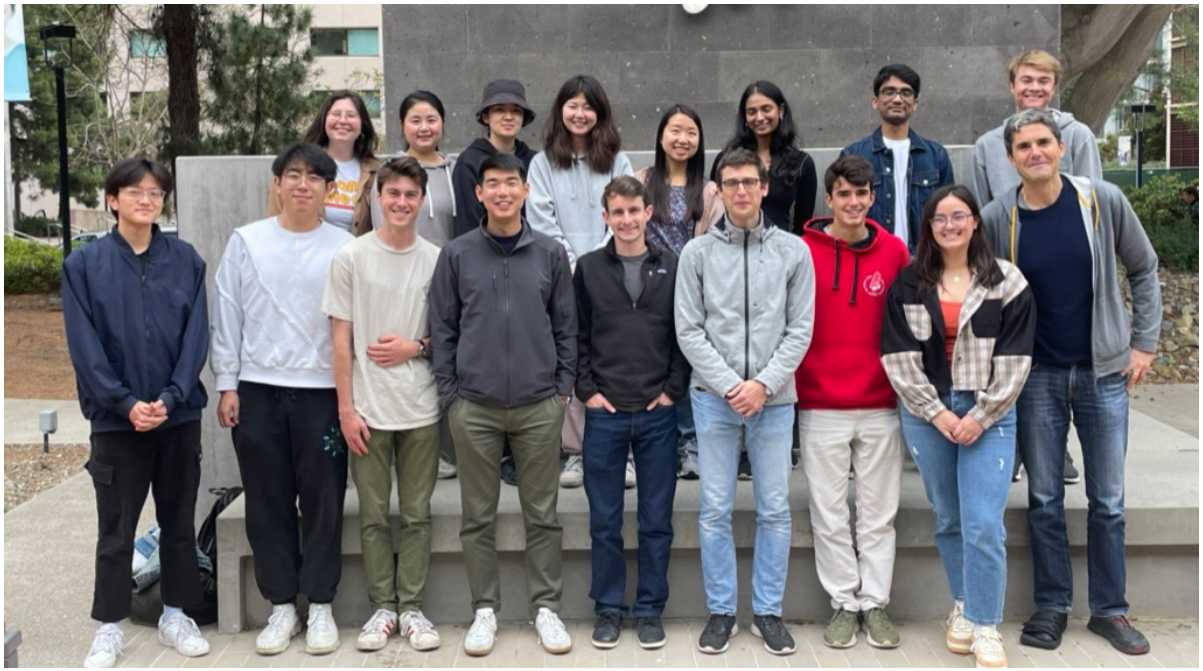
3D

- Simple tools of inorganic/supramolecular/polymer chemistry → complex biological assemblies with emergent properties (e.g., dynamic, responsive, reconfigurable and self-healing) and functions.

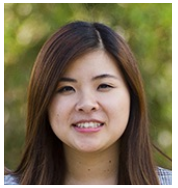
- High structural order ≠ no or low structural flexibility (and vice versa).

- Simple design ≠ simple outcome. Unusual emergent properties and functions are sometimes one small modification away.

FUTURE GOAL: To design scalable protein-based materials with desired physical/mechanical properties that can be evolved in living systems



Jake Bailey



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