Center for Bio-Inspired Energy Science (CBES)
EFRC Director: Samuel I. Stupp
Lead Institution: Northwestern University
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***Mission Statement**: To develop the next frontier in soft materials relevant to energy challenges by designing structures that emulate functions we see in biological systems.*

Soft materials are normally composed fully or partially of organic matter and the best examples are polymers, which have had an enormous impact in energy relevant technologies, particularly energy savings in transportation, manufacturing, infrastructure, and construction, among others. The next challenge is to learn how to synthesize soft materials with the capacity to interconvert energy forms, for example the way muscles convert chemical to mechanical energy in living organisms, or the way plant leaves optimize light to chemical energy conversion in a resourceful way to synthesize chemicals. Our vision is that basic science research in this area can lead to artificial materials that rival living ones in the remarkable and useful ways they manage energy. Our proposed research program specifically tackles the next big challenges in synthetic design of soft materials, namely learning how to encode in them molecularly the ability to transduce energy forms and even move autonomously in ways that are characteristic of "living matter". We approach this enormous bio-inspired challenge through bottom-up chemical design and synthesis combined with top-down engineering strategies, computation, and theory to create novel functional systems. The goal is to develop through basic science new opportunities around the concept of "robotic soft matter", denoting its autonomous ability to rapidly perform mechanical, optical, or chemical tasks with only small inputs of electrical energy and without the use of complex hardware. Equally important is learning to create "photosynthetic matter", which requires systems structured holistically to enable efficient chemical production using visible light. Our targets to create robotic and photosynthetic soft matter are extremely relevant to future modalities in manufacturing and chemical production, two of the greatest users of energy. Our cross-disciplinary investigations focus on bio-inspired research in the following areas.

Multi-Scale Synthesis of Artificial Muscles **(inspired by energy transduction in muscles)**

Muscles are composed of soft materials that have fast mechanical responses to chemical inputs. We have already demonstrated the ability to create soft robotic materials that mechanically respond to thermal or light inputs, but at relatively slow response speeds. Our aim now is to explore the upper limits of response speed in these systems, to make them fast-acting. Our approach will include both molecular synthesis and top-down architectures of the structures.

Magnetic Morphogenesis **(inspired by biological development)**

During biological development, protein signals mediate the morphogenesis of large collections of cells into specific shapes that create functionality. We aim to create the same level of control over synthetic soft matter using magnetic fields that actuate motion at nano, micron, and millimeter scales. We plan to use morphogenesis to induce directed locomotion and actuation.

***Autonomous Soft Microrobots* (inspired by living cells)**

Living cells navigate complex environments to perform diverse functions by integrating the capabilities of sensing, actuating, computing, and communicating. Similarly, we envision developing shape-shifting "microrobots" that move autonomously and adapt their motions in response to both environmental cues and interparticle signals. Microrobots with encoded functions are potentially desirable for distributed sensing or healing/repair tasks in energy-relevant materials such as battery electrolytes, polymer membranes, and catalysts.

***Hierarchical Structure-Mediate Photocatalysis* (inspired by the spatial organization of functional molecules in biological systems)**

Biological photosynthesis occurs in highly structured environments where the position and order of the components play a key role in the overall efficiency of multiple energy and electron transfer steps. Focusing on fundamental questions regarding the design of photocatalytic materials with bio-inspired spatial organization, we will explore how hierarchically assembled synthetic materials can be used to emulate the light-driven reactions found in biological systems.

***Mechanical Enhancement of Photocatalysis* (inspired by leaves)**

Leaves use mechanical forces to physically rearrange their chloroplasts to control photosynthetic output. We recently discovered surprising changes in the visible light absorption spectra and photocatalytic activity of hydrogels which depend on subtle changes in supramolecular packing. We will explore the potential impact of mechanical forces on the performance and control of soft matter encoded for photocatalytic activity and the possibility of accessing non-equilibrium photocatalytic states using mechanical energy.

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