Boston University
Boston, MA
Jennifer Bhatnagar, Pamela Templer, Lucy Hutyra, Jeff Geddes
$1,000,000

Rules of Life in the Urban Biome

Cities are expanding around the world, with unexpected impacts on the non-human organisms that live there. Recently, it was discovered that urban trees grow four times faster than rural trees, despite there being a multitude of environmental stressors in cities and the loss of typical belowground mechanisms for nutrient acquisition, stress tolerance, and pathogen protection. This project will test the hypothesis that urban trees operate by a different “rule of life” than rural trees, uniquely taking advantage of aboveground atmospheric pollution as a source of nutrients, water, and stress protection.

To test this hypothesis, the first study of its kind will determine how nutrients and water are acquired by city trees using a recently established, model urban-to-rural tree gradient. Through a combination of field-based nitrogen, water, and atmospheric chemistry measurements, plant and microbial biochemical analyses, plant surface microscopy, and air pollution manipulation experiments, this project will establish a foundational understanding of tree resilience and growth strategies within urban ecosystems. The data generated will provide new knowledge about the physiological capabilities of organisms under extreme environmental stress and the impacts on ecosystem services they provide.

Emory University
Atlanta, GA
Nic Vega, Levi Morran
$1,200,000

Experimental epidemics and pathogen evolution in heterogeneous populations of hosts

This project will use the small animal model *Caenorhabditis elegans* to study how diseases spread. *C. elegans* is an ideal candidate for these experiments because it is easy to work with, so that epidemics can be played out many times in controlled laboratory experiments, and the spread of diseases in these experiments closely mirrors real-world scenarios. In real life, diseases do not spread uniformly. First, some individuals spread a disease more than others, and some are more susceptible to catching it. This variation is known as heterogeneity, where individuals have different traits. Additionally, transmission is stochastic, meaning that while the probability of exposure causing an infection can be described, the actual outcome is uncertain until measured.

These sources of variation are known to be important, but real-world epidemics are difficult to measure, leaving gaps in understanding how heterogeneity and stochasticity shape outbreaks. By using worms, controlled conditions can be created to observe exactly how diseases move through populations, and similarities and differences can be noted when the same epidemic is run multiple times. This approach provides a uniquely detailed picture of the inner workings of epidemics, from which better models can be created.

The goal of this project is to uncover how variation in shedding, susceptibility, and behavior influence the course of epidemics and the evolution of diseases. With this knowledge, better strategies for controlling outbreaks in the future can be developed.

The George Washington University
Washington, DC
Sandy Kawano
$1,400,000

Integrating 3D technology, engineering, and biology to provide new insights into the evolutionary transition from water to land in vertebrates

Determining how vertebrates (animals with backbones) first moved onto land is central to understanding human anatomy yet remains an enigma. Prehistoric fishes are theorized to have had bones too weak to crawl onto land, so the shift from fins to limbs may have been a necessary evolutionary innovation to enable tetrapods (vertebrates with four limbs) to make the transition from water to land roughly 375 million years ago. However, fossil evidence suggests that terrestrial walking may have occurred almost 50 million years before tetrapods originated and living fishes can move on land without major terrestrial adaptations typical of tetrapods, potentially revealing alternative strategies for amphibious locomotion.

The project examines the core requirements for terrestrial locomotion by developing computational models to estimate the locomotor capabilities of extinct animals and deciphering the novel features of fish bones that enable numerous living species to leave the water's edge. Living salamanders and amphibious fishes will be used as functional models of their now extinct relatives, as they exhibit similarities in morphology and ecology. Fossil morphology from extinct specimens will be incorporated into the computational models to help resolve long-standing debates about when and how vertebrates first moved onto land.

The project integrates 3D technology, engineering, and biology to pioneer work on the functional diversity of bones and advance high-impact discoveries related to amphibious robots for autonomous exploration, bioinspired prostheses, and much more.

Northwestern University
Evanston, IL
Mahdi Hosseini, Yanbei Chen, Selim Shahriar
$1,300,000

Testing violation of quantum linearity induced by gravitational self-energy

Recently, it has been proposed that an inherent non-linearity in quantum mechanics may be induced for any massive object due to its gravitational self-energy, which, according to the Schrödinger-Newton Equation (SNE), would depend on the spatial distribution of its wave function. The signal predicted by this theory of quantum non-linearity (QNL) is extremely small, and no experiment to date has come close to achieving the requisite sensitivity. However, recent work has shown that it is possible to realize an optomechanical system able to detect a shift in the system's resonance frequency caused by QNL and distinguish it from all possible sources of noise, both quantum and classical. This team of researchers from Northwestern University and the California Institute of Technology will build and test such an ultra-sensitive optomechanical system, in the form of a quantum tweezer, with extreme isolation from the environmental noise. Experimental validation of QNL resulting from the SNE would result in a paradigm shift in our understanding of nature. Specifically, it would establish that at some scale gravity does behave classically. It would also confirm what appears to be the presence of interactions between distinct and parallel realities inherent in quantum theory, without violating causality. A null result would invalidate the SNE, disprove the existence of mutual gravitational energy between parallel realities, and lend credence to the idea that gravity must indeed be treated quantum mechanically.

Purdue University
West Lafayette, IN
Arnab Banerjee, Alexandra Boltasseva, Vladimir Shalaev, Pramey Upadhyay
$1,200,000

Uncovering elusive Kitaev topological states with strain engineering using metasurfaces

Quantum spin liquids represent an exotic and highly promising state of matter that could revolutionize the field of quantum computing by providing a robust, and scalable platform for topological qubits - a transformative quantum computing architecture. However, a critical barrier has remained: the elusive non-abelian states that underpin topological quantum phenomena have proven frustratingly difficult to observe experimentally. This team from Purdue University will pursue a groundbreaking approach to overcoming this obstacle by utilizing an innovative concept of metasurfaces that can effectively control both the coupling to light and the strain induced in exfoliated two-dimensional quantum spin liquid candidate materials. They plan to combine high-resolution cryogenic Brillouin-Raman scattering setup to probe the excited states in a mechanically strained topological quantum magnet to mimic intense magnetic fields which breaks apart the Raman spectrum into fractionally quantized non-abelian energy states. The key innovation lies in their ability to observe the Majorana Landau Level spectra – a hallmark signature of the highly desired non-abelian anyons - which has never been directly demonstrated. These experiments will push the boundaries on strain engineering that could enable high effective fields which are impossible to reach using even the most expensive superconducting magnets.

Rice University
Houston, TX
Shengxi Huang, Alexey Belyanin, Anna-Karin Gustavsson, Junichiro Kono, Yuji Zhao
$1,200,000

Superradiant Super-Resolution Imaging

A team of researchers at Rice University and Texas A&M University aims to revolutionize imaging by harnessing superradiance, a many-body quantum-optical process, in molecular and nanomaterial assemblies. The diffraction limit of spatial resolution in imaging can be circumvented in super-resolution imaging (SRI) and single-molecule tracking (SMT), whose precision is improved by increasing the number of detected photons. However, in classical imaging, such precision has an ultimate limit. Also, there is a tradeoff between spatial resolution and temporal resolution: to resolve finer structures, imaging is slower, and to achieve faster imaging, spatial resolution is compromised. These fundamental limits in classical imaging can be surpassed by leveraging superradiance that cooperatively enhances photon emission rate. The researchers will study and control superradiance in molecules and solid-state nanomaterials for fluorescence imaging, which can lead to unprecedented spatial resolution, temporal resolution, and localization precision, simultaneously, in SRI and SMT. This project will address several fundamental questions in quantum optics, pioneer the use of quantum optics and novel quantum materials in biotechnologies, and transform bioimaging, quantum sensing, and materials engineering. The outcome will be a new approach that demonstrates a quantum leap in imaging. This will profoundly impact the way one images, tracks, and senses single molecules, nanoparticles, and a plethora of materials, catalyzing scientific discoveries in a variety of fields.

University of Wisconsin – Madison
Madison, WI
Betül Kaçar, Brian Pfleger, Jean-Michel Ané
$1,300,000

Past as Prelude: Preparing for an Uncertain Future Shaped by Nitrogen

Every organism alive today is a product of ~4 billion years of life's evolutionary past on our planet. The history of life is one of absolute survival in the face of temperature extremes, catastrophic impacts, desiccation, and famine. This project will explore the untapped bioinformatic resource of life's remarkable evolutionary history in ways that may be applied to solving the problems that society faces, starting with the collective dependence upon nitrogen.

All life depends on a single microbial enzyme called nitrogenase to 'fix' atmospheric nitrogen into a form that can be used to build new cells. Current global nitrogenase activity supports nearly half of all food production needs, leaving at least half of the food consumed vulnerable to environmental, industrial, and ecological constraints. Civilization depends on developing sustainable methods to produce fixed nitrogen. It is postulated that a new molecular paleontology approach can help mitigate this unprecedented and untenable risk to which all are vulnerable for the first time.

The project will experimentally build and assess a complete natural history of an enzyme's diversity to understand how it has persisted through upheavals in atmospheric chemistry and surface temperatures over Earth's history. A unique disciplinary synthesis combined with one-of-a-kind high-throughput methods will be developed to resurrect and characterize a vast library of extinct and artificial sequences. This transformative research initiative aims to uncover billions of years of nitrogenase diversity and discover new possibilities for supplying essential nitrogen to the biosphere while stabilizing critical facets of ecological and agroeconomic systems.