RESEARCH PROGRAM

Science and Engineering Abstracts for Grants Awarded in December 2020

Brown University
Providence, RI
Pradeep Guduru, Jacob Rosenstein
$1,000,000
December 2020

A pair of researchers at Brown University will develop a ten million frames-per-second infrared (IR) microscope, which could measure highly transient, localized temperature fields in materials at unprecedented temporal and spatial resolutions. The temporal resolution of the planned IR microscope represents an improvement of about four orders of magnitude over commercially available systems. A new image-acquisition architecture will be developed, which incorporates state-of-the-art advances in integrated-circuit design and nano-fabrication technologies to achieve image acquisition at ten million frames per second. The instrument consists of the design, fabrication, and integration of four sub-systems: a mercury cadmium telluride detector focal-plane-array (FPA) with 32×32 pixels capable of measuring temperatures over a range of 300K–1500K; a state-of-the-art cryogenic CMOS Read-Out Integrated-Circuit (ROIC) for simultaneous high-speed data acquisition from all pixels of the FPA; a custom-designed IR optical imaging system to achieve diffraction-limited spatial resolution; and, a cryogenic vacuum-chamber to house the FPA, ROIC, and some of the optics. The IR microscope is expected to open up avenues of fundamental scientific inquiry that are currently not possible. Three specific areas in which the instrument will provide a transformative measurement capability are: imaging the formation and understanding the mechanisms of individual "hot-spots" in shock-loaded energetic materials; understanding the mechanisms of adiabatic shear banding in heterogeneous materials and engineering their microstructures for unprecedented mechanical properties for protection against impact; and, studying friction at the scale of individual asperities and the development of predictive friction laws for modeling earthquake dynamics. The in-house system design will also result in intellectual property with significant potential for commercialization.

Colorado State University
Fort Collins, CO
Richard Conant, Peter Baas, Claudia Boot, James Henriksen
$1,000,000
December 2020

Life's most important biochemicals (19 of 20 amino acids, most sugars, etc.) are chiral – they come in one of two possible shapes that are mirror images of each other. The idea that the shape of an organic molecule – its handedness or chirality – determines whether it is biologically active or not has been an organizing principle of biochemistry dating to Pasteur's time and has largely been a closed book ever since. One 3D shape is super abundant (e.g., D-glucose) and the mirror image shape (L-glucose) is thought to be extremely rare or even non-existent in nature. However, a handful of recent reports have found L-glucose in nature. After critically considering these anomalies, this team from Colorado State University screened soil samples from across the campus. To their surprise, every single sample contained bacteria capable of consuming L-glucose.

This shadow biochemical economy has never been observed before. These results fundamentally challenge the existing paradigm on chirality, which is thought to be integral to life throughout the universe. The researchers will build on this groundbreaking work by determining the capacity of soil organisms to consume and synthesize a variety of L-sugars, describing their functions in cellular metabolism, and understanding how these processes facilitate microbial growth, survival, and persistence.

Texas A&M University
College Station, TX
Victor Ugaz
$1,000,000
December 2020

A key unanswered question in the origin of life involves identifying mechanisms that explain how very dilute concentrations of lipid precursors could spontaneously assemble to form protocells under prebiotic conditions. The small pore networks that permeate mineral formations near undersea hydrothermal vents have emerged as potential hot spots for these processes. But so far, the physical machinery needed to drive macromolecular synthesis and packaging in these settings remains a mystery. The PI recently discovered how chaotic thermal convection in hydrothermal pore networks can accelerate these chemical processes. He plans new fundamental research that builds on this discovery to understand how microscale chaotic thermal convection can orchestrate the assembly of protocells containing targeted nucleic acid cargo. These insights will lay a foundation to identify new pathways for the spontaneous emergence of metabolic and replicating systems. Starting with principal phospholipid cell membrane constituents, the research will identify flow states that promote assembly into micron-sized vesicles from initially dilute millimolar concentrations. Next, the PI will induce simultaneous polymerization and encapsulation of nucleic acid cargo within the synthesized vesicles. Finally, protocells containing polymerized nucleic acids will be isolated and analyzed using single-cell multi-omic profiling methods. This screening will, for the first time, rationally link the physical domain of transport phenomena in hydrothermal microenvironments with the biochemical realm of protocell formation and nucleic acid synthesis, making it possible to identify and select conditions that favor assembly of specific sequences.

Tulane University
New Orleans, LA
Diyar Talbayev, Denys Bondar
$1,000,000
December 2020

Time-domain superoscillations (SOs) occur when several light waves of different wavelengths combine, over a brief time interval, into an almost perfect destructive interference. During this short interval, the electric field is not exactly zero, but can perform a weak oscillation, the superoscillation, that is faster than the original individual light waves. This counterintuitive property does not contradict any laws of physics and has already enabled breakthrough resolution enhancements in optical microscopy in the spatial domain. In the time domain, optical SOs of the electric field of light have not been demonstrated. A pair of researchers at Tulane University will experimentally synthesize optical time-domain SOs for the first time, and assess their potential for breakthrough capabilities in spectroscopy, communications, and wavelength conversion. They estimate that SOs can enhance ten-fold the sensitivity of light to the out-of-spectral range optical absorption as they travel through an absorbing material. This promises the possibility of spectroscopic substance detection through opaque media, which would provide a new paradigm in remote optical sensing. Super-transmission allows SOs to travel over long distances in an absorbing medium. This could enable breakthroughs in communications, as in THz frequency wireless, where the main obstacle is the strong THz absorption in the atmosphere. Yakir Aharonov at Chapman University predicted that the fictitious high frequency of SO can be converted into a real propagating harmonic by opening and closing a window at just the right times. The team will perform a version of the Aharonov experiment that could enable groundbreaking new sources of ultraviolet and shorter wavelength light.

University of California, Berkeley
Berkeley, CA
D. Kwabena Bediako, Michael Zuerch
$1,000,000
December 2020

Conventional crystals use individual atoms as their building blocks. A contemporary goal of synthetic materials chemistry is instead to use clusters of atoms that are subsequently arranged into a much longer-range pattern to form so-called superatomic crystals or supercrystals. Such materials have the potential to display properties that are distinct from those of atomic solids owing to the integration of multiple length scales as well as the emergent properties of the superatomic clusters themselves. To-date, atomically thin 'two-dimensional' (2D) superatomic solids have not been synthesized or isolated as freestanding crystals. A pair of researchers from the University of California, Berkeley want to create this materials paradigm with a specific focus on realizing a totally uncharted class of 2D magnetic solids that can be manipulated with ultrafast light waves. The team's approach exploits recently discovered highly tunable patterns in twisted (or moiré) bilayers of atomically thin materials. In stark contrast to other work on 2D materials, they seek these moiré architectures primarily as an atomic host/scaffold for long range chemical assembly. The researchers will combine synthesis of this highly tunable new family of materials with new ultrafast optical spectroscopy and imaging methods to probe both ground state and excited state magnetic behavior. Their bottom–up approach to inventing high-density ultrathin magnets that will be optically addressable at ultrafast rates overcomes a critical current limitation in ultrafast coherent magnetism. This project promises to open a new realm of tera- to petahertz magnetic switching, with transformative ramifications for ultralow-power electronics, ultrafast compact memories, and artificial intelligence.

University of North Carolina at Chapel Hill
Chapel Hill, NC
Charles Carter, Abigail Knight, Qi Zhang, Hiroaki Suga
$1,000,000
December 2020

Life requires intimate coordination of two different kinds of polymers. Nucleic acids carry genetic information as genes, which are the blueprints for making specific proteins. Proteins, the poly-amino acids assembled according to the genetic code, have vastly more diverse and complex functionality. Replication of genes—the basis of life's memory—requires a coded protein enzyme, suggesting that replication and genetic coding emerged together by some unknown cooperative process. Details of that process pose an outstanding challenge and paradox associated with unraveling the origin of life. Reflexivity—enzymes that translate the genetic code must, themselves, enforce the coding rules by which they were assembled—confounds that puzzle. The remoteness of life's origins complicates the design of experiments to reveal how genetic coding of peptide sequences could have arisen from simple components. The UNC team hypothesize that solving this classic "chicken and egg" problem implies the existence of historical context: all successive versions of the code were interpreted by a pre-existing machinery: an "egg laid by a bird that was not a chicken." They will investigate a novel hypothesis about that primordial translational machinery by showing that templating of anticodons in the tRNA acceptor stem by nucleic acid sequences containing sequential triplet codons equivalent to those in contemporary protein synthesis, may have sufficed by itself to accelerate peptide synthesis without any other catalyst, while creating a selective advantage for a protoribosomal catalyst. That experimental translatomics platform facilitates posing testable questions in a uniquely plausible context. The team will use the platform to investigate the combinatorial chemistry underlying genetic coding by measuring rates and specificities of dipeptide synthesis. They will further seek a heretofore unknown connection between coding and catalysis by testing whether extant protoribosomal machinery, which appears not to enhance peptide bond formation, can do so if the two adaptors are templated. The researchers aim to be first to address a crucial step in the transition from random, spontaneous chemistry into the highly organized computational networks characteristic of biological information transfer, reshaping our understanding of how life evolved on earth.

University of Oregon
Eugene, OR
Eric Corwin, Ivan Corwin
$1,000,000
December 2020

Diffusion is pervasive in the natural world. Over one hundred years ago Einstein created a remarkably simple and powerful theory describing the behavior of a single diffusing particle. That theory has since been applied countless times to successfully model widely disparate systems. However, researchers from the University of Oregon and Columbia University believe that for large numbers of particles diffusing in the same environment, this theory does not work because it neglects the effects of the shared environment in which all particles coexist. As a consequence, the Einstein theory dramatically fails to predict the behavior of extreme diffusion, i.e., outlier particles which have moved the farthest from their starting points. The team plans to demonstrate, both experimentally and theoretically, using very different systems of colloids, fluorescent dyes, and optical photons, that systems with identical diffusion coefficients can have radically different outlier behavior dependent on the microscopic correlations present in the environment. By synthesizing their experimental measurements and theoretical results they hope to define a new extreme diffusion coefficient to succinctly describe these behaviors and thus create a new theory of Extreme Diffusion. Understanding the behavior of outliers will have wide ranging applicability to physical, biological, epidemiological, economic, and social systems where outliers often determine behavior.