MOLECULAR MACHINES

Aaron King

Keynote Speakers

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Introduction

Foresight Molecular Machines Group

An invitational group of scientists, funders, and institutional allies who cooperate to advance molecular machines, progress toward atomic precision for applications in energy, medicine, material science, and space development, and Richard Feynman's vision of nanotechnology. This group is chaired by Foresight Fellow James Cooper, University of Reading.

DNA origami, automated organic chemistry, atomically precise manufacturing, and molecular force spectrometry are just some of the topics discussed. These inventions are the catalyst that can spark breakthroughs in medicine, manufacturing, energy efficiency, and robotics. Both synthetic and biological components are of interest at the nano scale, and ideally we will get to the point of building molecular machines with the strength of synthetic materials but the robust self-assembly properties of organics. Seminars range from recorded keynote presentations, to open brainstorms on long-term progress, to off the record funder presentations, and smaller mixers.

This report gives an overview of our 2021 recorded seminars, including a favorite slide, and a link to the full written summary and recording for those who wish to learn more.

Foresight Institute

Foresight Institute is a 30+ year-strong San Francisco-based institute to advance crucial science and technology for the long-term flourishing of life. We believe that, in addition to directly addressing existential risks, one relatively neglected area for impact is to directly support differential technology development in areas that make great futures more likely. We focus on working groups to advance:

- Molecular Machines for atomically precise control of matter
- Biotech & Health Extension to reverse aging and improve cognition
- Computer Science to secure decentralized human AI cooperation
- Existential Hope to catalyze beautiful futures

I invite you to apply to join, support our work, or contact me with feedback, questions, and suggestions.

Thank you for your interest in our work,

Allison Duettmann
President, Foresight Institute
a@foresight.org

Molecular Machines Group Launch

James Cooper, University of Reading   January 23, 2021

Summary

James Cooper discusses the Foresight Institute, future directions, and goals for the Molecular Machines group. We seek to create an inclusive community of forward thinkers and doers who are interested in nanotechnology. A fantastic array of projects and contributors is lined up and more interesting projects are always being added. Attend the online discussions to get firsthand knowledge of exciting new developments of advances such as DNA origami, molecular rotors, and atomic force microscopy.

Opportunities

- Identify the fundamental concepts that govern how molecular machines behave
- Interface molecular machines with nano- or microscale assemblies
- Create molecular machines that operate in concert
- Discover applications of molecular machines

Access the full summary and recording

The advent of artificial molecular machines

David Leigh, University of Manchester   February 20, 2021

Summary

David Leigh starts with an investigation into the vision required for scientific progress. A scientist needs to find a problem interesting enough that is worth spending time on, yet sufficiently difficult that it hasn't been solved. One must recognize that the time has come for solving that problem. Nanotechnology lost its way in the '90s due to over-complex ideas of nanofabrication.

He continues with a description of a molecular machine that can create stereoisomers in a programmable fashion. Finally, a nanoscale molecule assembler has become reality. Although it is simple, it is a new format of catalysis and represents a fundamentally different process. Leigh's group is working on other molecular machines that take lessons from biology and improve upon them.

Opportunities

There will likely be breakthroughs in the next 5 years in compartmentalization, organization on surfaces and interfaces, and systems chemistry. Further out, 15 years or more in the future - artificial life systems, a reinvention of catalysis, and a killer application that produces true value from nanotechnology.

Access the full summary and recording

Kinetic vs. thermodynamic stability in non-equilibrium chemistry

Raymond Astumian, University of Maine   February 20, 2021

Summary

This was a talk about thermodynamics vs. kinetics and a proposal for a mechanism that can catalyze chemical reactions using physical force. The mechanism is driven by redox reaction cycles and can occur at room temperature in a single vessel. It works by shifting the position of cyclophane rings during each redox phase to be closer to each other, physically forcing two molecules into close contact and bonding them together. This is very similar to how ATP synthase works.

Unsolved Problems

The rings must be mounted onto the device such that an A ring and B ring are on opposite sides of the catalysis rod (shown below). If two A rings are on the device, it will not work.

Rotation of the target molecules must not occur while mounted on the rings, and the rings must not rotate while on the rod.
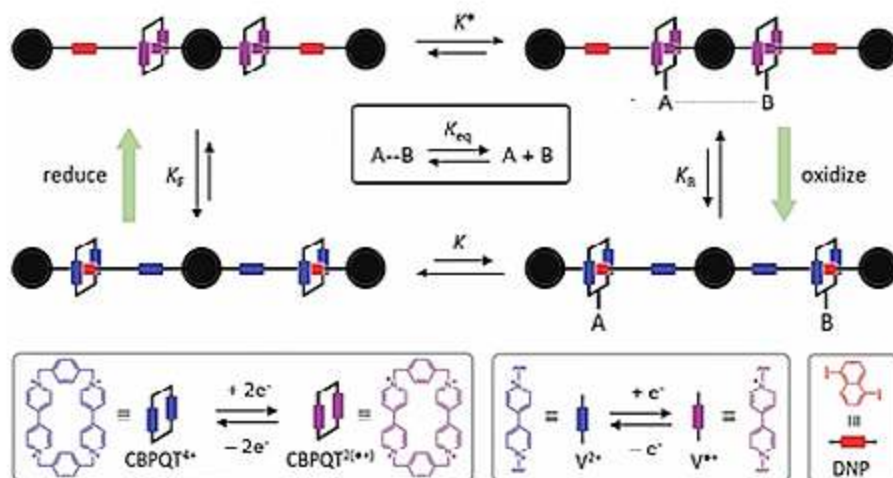
Access the full summary and recording

Molecular machines fueled by light that operate away from equilibrium

Alberto Credi, University of Bologna   February 20, 2021

Summary

Most molecular devices exploit equilibrium properties - this is not surprising because the equilibrium state is the easiest state to obtain. However, living systems operate away from equilibrium. The systems that support life are non-equilibrium processes, and it's typically not a good sign when an organism reaches equilibrium.

Rotaxanes are attractive molecules for molecular machines. The threading and dethreading process of rotaxane machines is crucial for their functionality. Light can be used to control the threading of rotaxanes by attaching azobenzene to the ends of molecular rods. Non-equilibrium states can be achieved by using light-induced rotaxane machines to drive reactions in one direction.

Opportunities

In the near term (1-5 years), photochemically driven rotary motors are being investigated. There is also interest in intramolecular storage of light energy.

The medium term (5-15 years) goal is the conversion and storage of light energy into chemical energy. Membrane and vesicle technology could be helpful for this goal.

The long term (10-30 years) goal is to pump molecules in and out of cells.

Light activated supramolecular pumps: a minimalistic approach
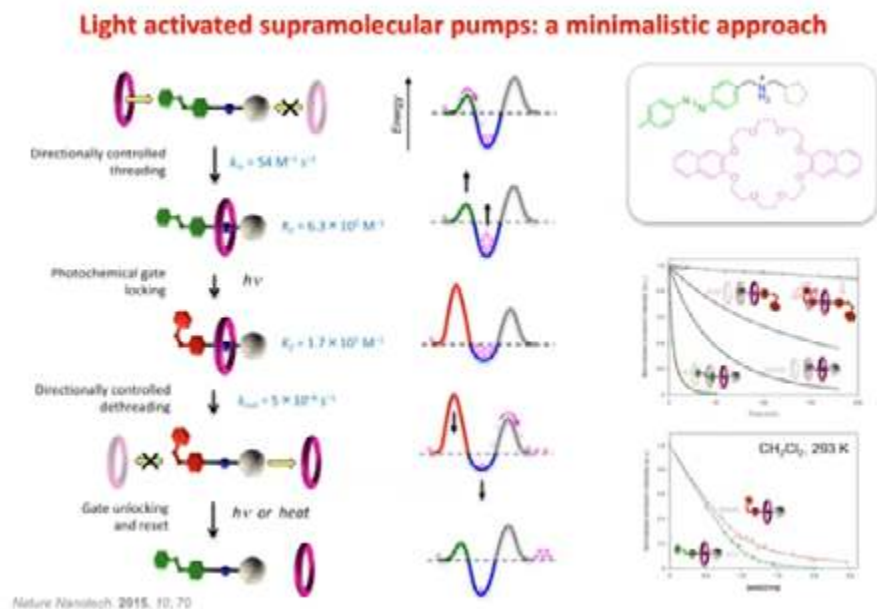
Access the full summary and recording

Enabling applications of nano/micro machines brainstorm

Ayusman Sen, Penn State
Amar Flood, Indiana University
Marty Edelstein, Agua Via
Gayle Pergamit, Agua Via

February 25, 2021

Summary

Molecular machines could be used for autonomous nanomotors, motion-based targeting, information processors, rheology, catalysis, sensors, and pumps. Nanomotors attached to surfaces can be used to deliver drugs or sense toxic substances. Perhaps some kind of on-demand insulin delivery could be assembled.

Nanofluidics should progress from fundamental knowledge to a technology base, then finally to technology integration with partners. This is organization that should happen at a governmental or systemic level, maybe from ARPA or the Department of Energy.

Nanoelectrical mechanical systems may turn into a large array of devices. These machines can be subgrouped by function then by using machine learning we can find compositions of machines that yield high value.

The pipeline of an idea goes flows as such; research - proof of concept - lab production - prototype production - capacity in production environment - demonstration of production rates.

Example: Vision for Multi-investigator Center
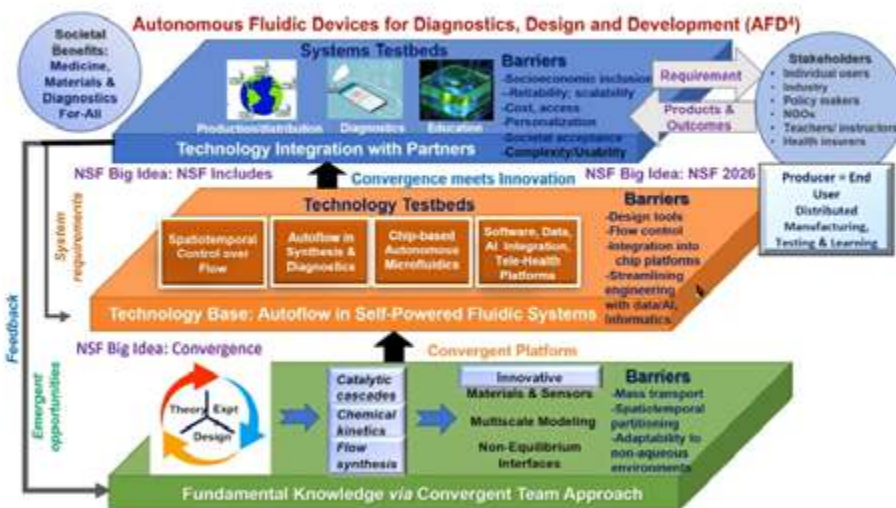
Access the full summary and recording

Molecular machines applied in medical treatment

James Tour, Rice University   **March 19, 2021**

Summary

Professor James Tour of Rice University presents a novel molecular robot that was developed thanks to crucial experimental work with Robert Pal of Durham University that targets a specific cell, and then drills into and through the cell wall causing the cell guts to spill out. Preliminary targets are either a cancerous cell or an antibiotic-resistant bacterial cell. The mechanism is rapid cell death via mechanical tearing, not a chemical mechanism, that is highly resistant to both cancer mutations and also antibiotic-resistant bacteria mutations. Neighboring cells are left unaffected.

While this technology is available in vitro now, Professor James Tour expects this technology to be clinically proven and also available to no-option end of life patients within 1-5 years, with full approval available in 5-15 years.

Opportunities

• Clinical proof, translation, and no-option patient use is achievable in 1-5 years
• We need the world to open back up after COVID and hire synthetic chemists
• Should investigate suitable scale-up operations for synthesis
• Figure out how to select a specific target molecular motor

Opening of lipid bilayers with nanomachines. Molechanical (molecular-mechanical) action
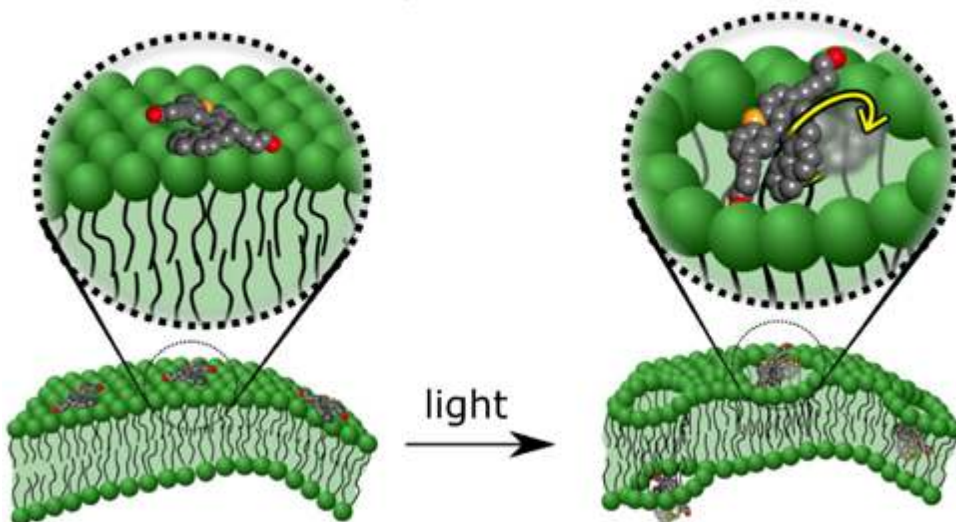
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Molecular machines that work at all scales

Nicolas Giuseppone, University of Strasbourg   March 19, 2021

Summary

Typically we see from nature that molecular machines can be assembled into larger assemblies in order to extract work from them. One example is the myosin/actin filament contraction in muscle cells.

A synthetic contraction monomer element (i.e. [c2] Daisy Chain rotaxane) was developed and integrated into a polymer form to mimic the action of muscle cells. Light-driven rotary motors were also integrated with polymer chains and networks to convert rotational motion into linear motion. These systems are for instance part of a design to be put into living cells to perform mechanotransduction. These units can also be networked together to create mechanically active gels. In addition, rotary modulators can be added to contract and expand the system in a controlled and reversible fashion.

Opportunities

In the short term we should pursue fundamental research on hierarchical mechanics with artificial nanomachines, reducing the chemical wastes coming from their actuation, controlling their speed of actuation, improving the work produced, and controlling the fatigue of materials.

In the medium term - can we apply the work of molecular motors at the macro scale? Emergent challenges include developing chemical fuels, biomaterials in vivo, storing and converting energy, and programming sequential tasks.

In the long term, we should see multidisciplinary approaches and eventually discuss with industry for innovation of new products.

Access the full summary and recording

Protein based assemblies and molecular machines

David Baker, University of Washington   April 16, 2021

Summary

David Baker from the University of Washington presents breakthrough advancements in de novo protein design. Deep learning pattern recognition hallucinates the desired protein structure and also generates the correct peptide sequence for accurate folding, and predicted proteins are highly transferable to actual proteins produced in a lab.

Results of deep learning are easily transferable to the production scale on a rapid timeline of weeks. Applications are vast in breadth and depth. Present interests are focused on designing protein assemblies for molecular machines. Components have been successfully assembled and although results are not yet satisfactorily validated, they appear to perform controlled work. Another application is targeting cells with a more accurate computational recognition method. Finally, clinical trials that are underway of a novel vaccine that is highly effective against coronavirus.

Opportunities

- Universal Vaccines - We can design a flu vaccine where 1 shot gives a lifetime of immunity from the flu. Also, we can protect against intentional acts of bioterrorism with rapid two-week development times until clinical trials.
- Larger Alphabet - Instead of only 20 amino acids from nature, we can design thousands of novel amino acids.
- Advanced Drug Delivery - We will be able to target disease cells with more precision and deliver drugs to target cells that were previously inaccessible.
- Smart Therapeutics - We will be able to perform calculations within the body. This will enable for example smart targeting that differentiates between subsets of the same types of immune cells.
- Next-Generation Materials - Silk, abalone shell, tooth, horns, and hair are all protein-based. We can approach ecological issues by mimicking or creating new types of materials.
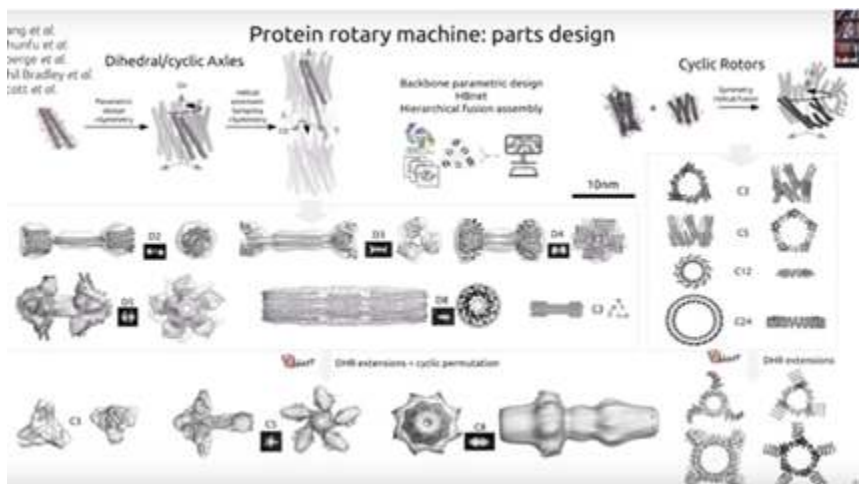
Access the full summary and recording

AMO's program in atomically precise manufacturing and nanocarbon metals

Tina Kaarsberg, DOE **May 3, 2021**

Summary

An overview of projects spearheaded by the Advanced Manufacturing Office (AMO) of the US Department of Energy. These projects, involving Atomically Precise Manufacturing, are part of a larger vision for energy efficiency. The diverse portfolio of projects includes molecular assembler tips, molecular lego, diamondoid tools, copper/carbon hybrid materials, DNA origami, and Microelectromechanical systems.

The hypothesis driving the AMO is that increasing control at the atomic scale is a pathway to greater energy efficiency. Atomically precise manufacturing is the next step in a long history of ultra precise manufacturing techniques. AMO recognizes that much of the cutting edge is at the nano or even atomic scale. Semiconductor manufacturing is one of many fields that will benefit from APM, and is likely the closest to commercialization.

The variations on SBIR topics tracks the evolution of AMO priorities. Many different projects were initiated over the years. One successful project was to create nanomembranes for oxygen generation. Another successful project involving catalysis discovered a detergent molecule. In 2018, STM lithography research was funded which has become the foundation of ultra energy efficient semiconductor device work. Nano-aluminum was also funded during this time and may become part of the APM portfolio.

Current projects overseen by AMO

- Dopants on silicon with STM - Atomic precision for microelectronics
- MEMS STM platform - Metrology for microelectronics
- 3D SPM Tip Sculpting - Has Non-SPM applications
- Molecular Lego - Has DOD Applications
- DNA Origami - Big Idea Proposal
- Metal Nanocarbon Composites - CABLE

Metal enhanced with nano-carbon→CABLE
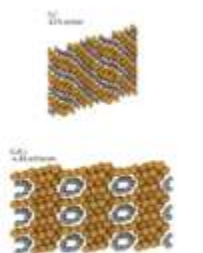
Atomistic modelling of Cu-rich carbon flakes and equimolar carbon sheets by Subramanian Sankaranarayanan ANL

EERE BIG IDEA 2020

CABLE: stands for conductivity-enhanced materials for affordable, breakthrough electric and thermal applications.

Prize — CABLE Conductor Manufacturing Prize

Workshop

Access the full summary and recording

Single molecule identification and detection via DNA nanotechnology

## William Shih, Harvard University   June 1, 2021

Summary

William is overseeing an effort to apply Synthetic Biology approaches to the development of self-assembling DNA nanostructures and devices for use in biomedical applications. To achieve structures of even greater complexity, his laboratory is pioneering methods for hierarchical assembly of these particles into three-dimensional networks with site-specific control over chemical functionalization and mechanical actuation.

DNA origami is a robust process for creating DNA structures using scaffold strands and free floating oligonucleotides. However, it can only be used for structures <100 nm in size. To work with larger structures, criss-cross polymerization can be used, amplifying an analyte signal to billions of times its size.

The first step is to detect the target sequence and convert it into an artificial record, called a nano-bean. The second step is to convert each nano-bean into a micro scale beanstalk, a large scaffold entity that can be detected easily. The key is to have a beanstalk formation process that is only ever initiated by the target nano-bean. Crisscross-cooperative growth uses DNA fragments built to only polymerize with each other on 3-4 base pairs. As the scaffold grows, the DNA is locked in place by making contact with successively further DNA fragments, creating a weave of DNA where base pairs further from the center are matched with each other.
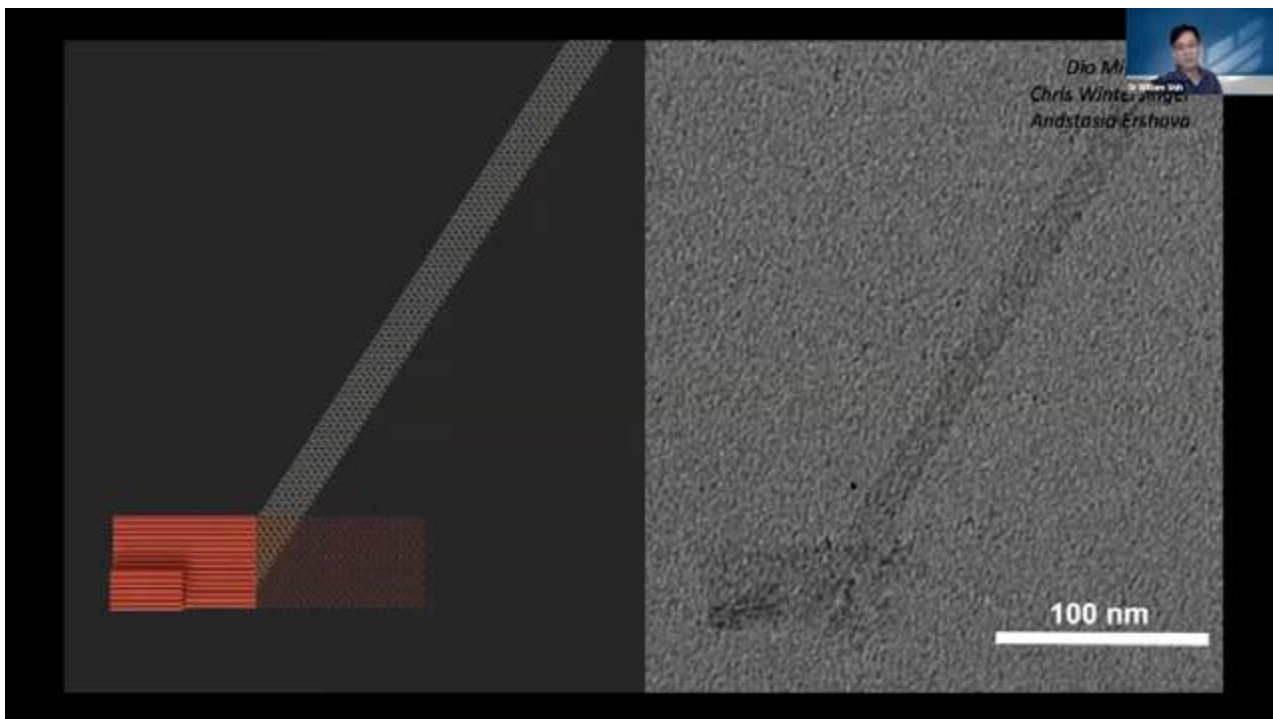
Access the full summary and recording

Molecular pattern recognition in DNA-based artificial neural networks

Lulu Qian, California Institute of Technology   June 1, 2021

Summary

How do we get molecular machines to recognize patterns and make smart decisions?

Neural networks are good at recognizing things. Also, the same network can be reconfigured to recognize different patterns. It has been hypothesized that neural-network-like computation occurs at the molecular level in cells.

One of the simplest types of neural network models is based on linear threshold gates, where the output is 1 if the weighted sums exceed some threshold. 10 years ago we developed a DNA-based 4-neuron Hopfield network using linear threshold gates. The network can recall a molecular pattern based on incomplete information. More recently, the system was scaled up from 4 bit to 100 bit by using a competitive "winner take all" method. One advantage is that negative weights are not necessary, because only the relative values of weighted sums matter. This simplifies the system and requires fewer molecules.

The DNA-based winner-take-all circuits can recognize molecular patterns even if they are heavily corrupted.

The mathematical function of a winner-take-all neural network can be implemented with biochemical reactions using DNA as a programmable substrate. These systems use strand displacement mechanisms to create dynamic interactions between molecules and perform information processing in a biomolecular environment.

Opportunities

We should investigate learning behaviors in DNA-based neural networks. For example, adaptive memories can be developed by utilizing inhibition or activation of weight molecules that encode a memory. This would lead to self-improvement in molecular machines, where input signals trigger responses that adjust the decision-making process for future pattern recognition.

A 100-bit 9-memory DNA neural network

K. M. Cherry and L. Qian, *Nature* (2018)
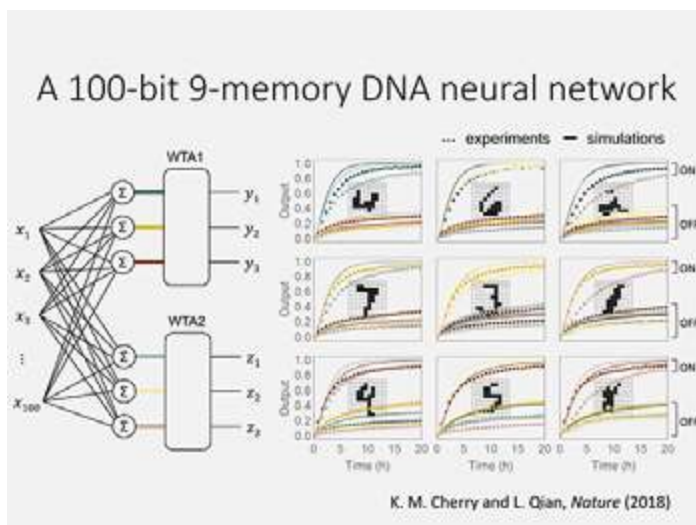
Access the full summary and recording

NSF Division of materials research: Where materials begin and society benefits

**Linda Sapochak, NSF**   **June 14, 2021**

Summary

Linda Sapochack shared her insights on the National Science Foundation's Division of Materials Research – what has been done, what projects are ongoing, and opportunities for the future. The new director Dr. Panchanathan has bold plans for the future of DMR and several key programs will be instrumental in carrying them out – the Materials Genome Initiative, Materials Research Science and Engineering, and Designing Materials to Revolutionize and Engineer our Future.

The Executive Office is keen on enhancing the Materials Genome Initiative, estimating the value of improved materials innovation at $123-$270 Billion per year. The Endless Frontiers act will assist with the NSF vision of research translation.

Linda has been spearheading 'square tables' for better communication and dialogue between funders, scientists, and engineers to accelerate progress and share data. She encourages interested parties to contact her and the NSF about these programs and the square table initiatives if they think it will be beneficial for them. The Materials Innovation Platform – DMREF on steroids – is meant for iterating between computation and experiment, and building a community around a problem. Samples, know-how, and tools are available for labs across the country.

Opportunities

The near and long term goals of the NSF are decided by the taxpayers, and the NSF encourages you to come to them with ideas about what you want to see in the future.
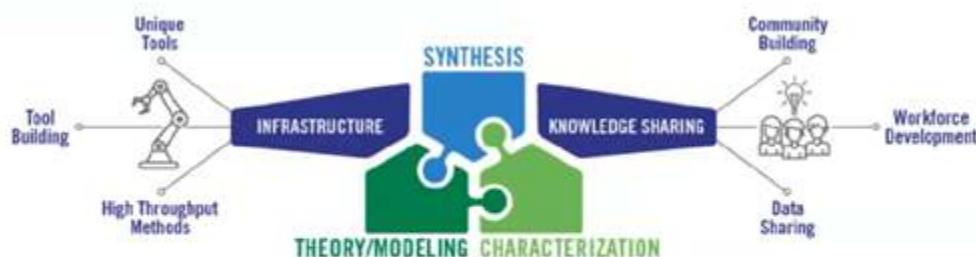
Access the full summary and recording

The first programmable turing complete chemical computer

Lee Cronin, University of Glasgow   **June 24, 2021**

Summary

Lee Cronin, a professor at the University of Glasgow, explains the Chemputer – a universally programmable device for synthesizing any molecule. The programming approach is part of a natural progression of any technology, and even though the backend is complex the end product helps simplify the process of using organic chemistry to produce any molecule desired.

Development is ongoing and as proof of concept, the chemical computer produced Diphenhydramine, Sildenafil, and Rufinamide all on the same machine and magnitudes faster than human controlled synthesis.

Lee postulates that with heater/chiller, filtration, phase separation, evaporation, column chromatography modules approximately 60% of organic synthesis could be covered. Adding low temperature, solid handling, and vacuum distillation modules boosts the capability to 95% of all chemistry operations.

Opportunities

The near term objectives for the chemputer are to carry out any organic chemistry operation, develop a universal code language for its operation, develop a library of universal methods, and make the system robust enough to handle human error. The long term objectives for Lee are to tackle the chemical origin of life and create chemputers on campuses across the country for easy scaleable specialty chemical production.

The ChemPU System Improves in VERSIONS

Access the full summary and recording

Controlling the machinery of life with synthetic photoswitches

Dirk Trauner, NYU   **July 15, 2021**

Summary

When attempting to manipulate cellular function, it's much easier to use the established regulatory pathways rather than building your own. Inserting photoswitches at key points in those pathways let us control cell function with light. The best location for such switches is on the membrane of the cell - easy to measure, open to light sources, and where most of the cell's regulatory proteins are located.

Voltage gated ion channels, ligand gated ion channels, pumps, actin and tubulin cytoskeleton motor proteins, nuclear hormone receptors, lipids, E3 ligases, and g-protein coupled receptors have all been successfully married to photoswitches so far.

A key molecule is azobenzene, which switches conformation based on exposure to either 500nm or 360nm light.

Tethering ligands to receptors using azobenzene molecules in the tether allows you to directly control bioactivity across a wide spectrum of enzymes. Rapid controlled initiation of downstream signaling can be accomplished with the flick of a light switch.

Opportunities

Medium term goals - the possibility to control things with input signals other than light. Using magnetic fields or ultrasound would be more penetrative. It should also be possible to put molecular motors on proteins.

Tethered photopharmacology for mGluR2
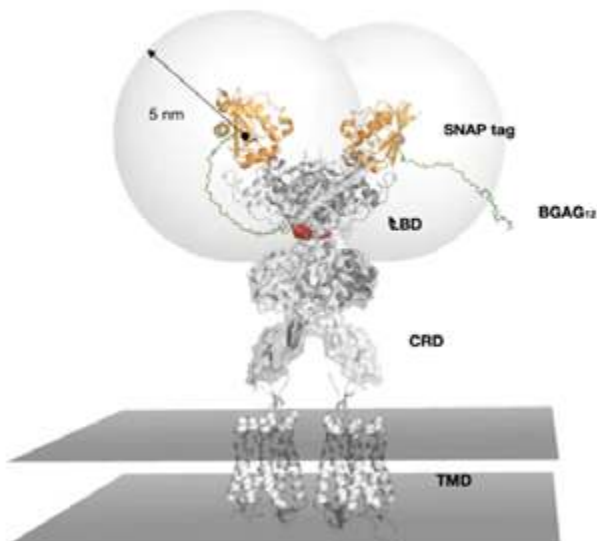
Access the full summary and recording

Molecular 3D parts and systems brainstorm

Adam Marblestone, Schmidt Fellow
Benjamin Reinhardt, Princeton   **July 30, 2021**

Summary

How do we frame concrete goals for future programs around systems of molecular machines? The current work needs to be part of a larger coherent vision.

The ribosome is the place to start thinking about integrated molecular machine systems. It is an assembly of various mechanisms that work together to produce complex nano-scale products. In practice, the ribosome uses RNA to assemble proteins via tRNA/amino acid modules. Building an artificial ribosome represents a strategic goal for molecular machines.

Opportunities

Going beyond the machines we see in nature, we should ask what biology cannot do then produce machines to fill that void. Constraints of biology are single bonds between blocks, noncovalent interactions, and a requirement for large scaffolding for small active sites. How can we assemble a complex interaction of molecular machines that overcome these constraints and yield exponentially more valuable results?

Let's do more than talk. PARPA is looking for a PM to run an artificial ribosome program full time.
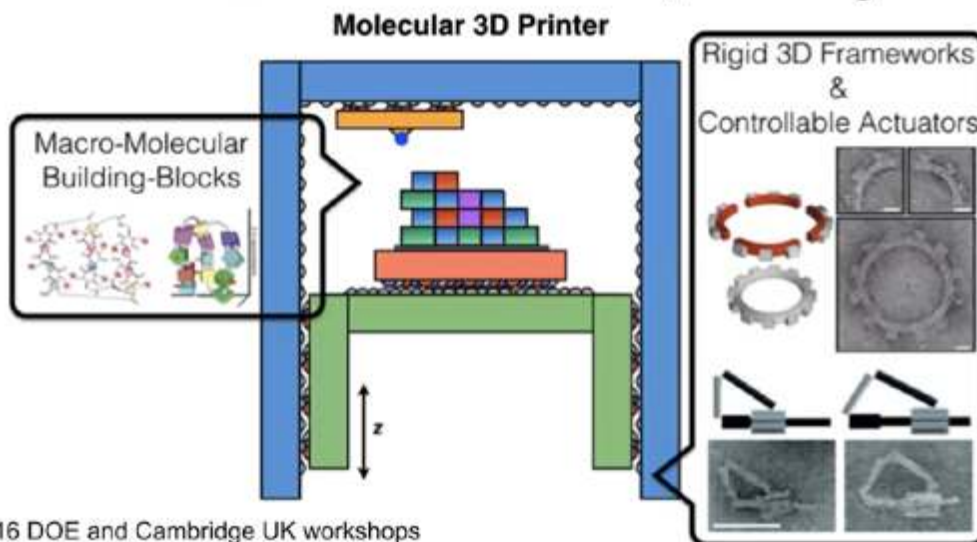
Access the full summary and recording

Probing synthetic molecular machines with atomic force microscopy

Anne-Sophie Duwez, University of Leige **August 26, 2021**
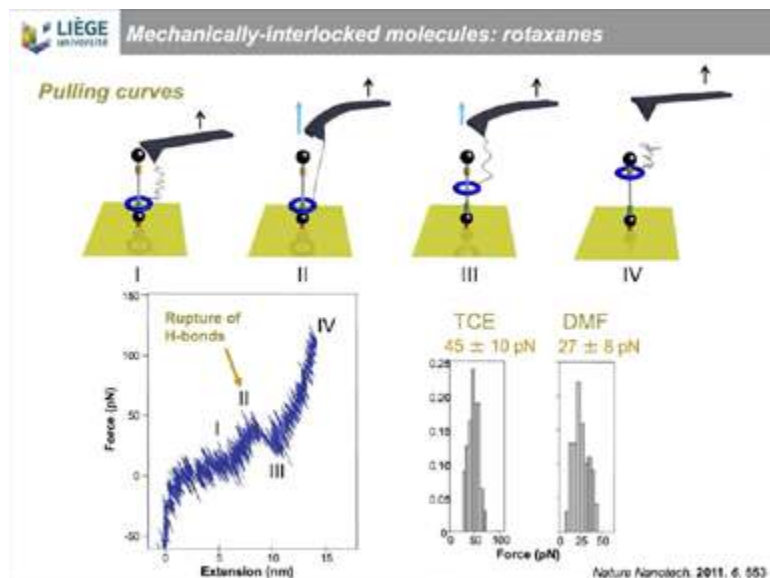
Summary

Anne-Sophie is using atomic force microscopy principles to develop a force spectrometer. This spectrometer can measure binding forces at the atomic scale by pulling molecules and reading extremely small force changes as they change configuration or break from the spectrometer tip. It has been used to measure ring/axle assemblies, rotaxanes, molecular rotors, and oligoamide helices.

When designing machines using single molecule components, will these obey the current laws or will we need to rethink how we view physics at these small scales? Furthermore, can we design small machines to surpass biological components in efficiency and strength?

Force spectrometry is a valuable tool for diagnosing the potential of molecular machines.

Opportunities

In the near term, we should be able to measure a molecule at work during a mechanical or chemical cycle.
In the medium term, we should be optimizing bonds and conformations to design more performant systems.
For the long term, we should focus on the concerted action of molecular machines, making molecular machines work together to create something greater than the sum of its parts.

Access the full summary and recording

Molecular Machines: Table of Devices

This table is a collaborative effort to give a detailed overview of Molecular Devices.

This spreadsheet covers 70+ journal articles, each describing a molecular device that might be useful as part of a more complex system. Each row of the table includes a diagram of the device, and summarizes the respective article.

The field of Molecular Machines is spanning many disciplines and is rapidly growing. The goal of the table is to allow individual researchers to get up to speed on work in related fields, with the hope to entice cross-collaboration to integrate individual efforts. Please contact Foresight Institute to contribute to the table.

User reviews:

"That is a major contribution. ... Thank you for your many efforts to move molecular machines forward."   Neil Jacobstein, President of the Institute for Molecular Manufacturing (IMM).

"Thanks for sharing the collection of articles ... Reviews and lists of key papers are definitely helpful for that initial context [when a new member joins our group], and again when we prepare to publish and have to write introductory text."   --Shawn Douglas, Department of Cellular and Molecular Pharmacology, University of California, San Francisco.

Molecular Machines Bountied Brainstorm

The Bountied Brainstorm aims to drive long-term progress on Molecular Machines by allows participants to ask open-ended questions, answer questions posed by others, and vote on the best answers. Foresight pays monetary bounties for each contribution and the best answers. You can find a selection of questions below, followed by a selection of three participant answers.

If you had $50 M to spend to advance progress on molecular machines, what would you spend it on?

What are design criteria for molecular machines that would enable a transformative application long-term, i.e. 30 years from now?

Commercial application/VC zone: is there any work relevant for progress on molecular machines that is in the zone of "not done, needs to be done, and we have the tools to do"?

What is your definition of a Molecular Machine? Describe your favorite example with its defining properties.

Which enabling technologies, tools, or techniques would you like to have that other fields could provide?

What does the field of molecular machines focus on too much/ not enough?

What is the best question to ask to drive long-term progress on molecular machines?

In this complex field, what are techniques that can be applied to molecular machine design or production that is actually simple? Chemistry, production techniques, biological hacks, _____, ?

Can existing silica infrastructure be used to interplay and boot-strap the first diamondoid structures?

[Brainstorm Answers 1](#)
[Brainstorm Answers 2](#)
[Brainstorm Answers 3](#)