Report of the

Alternative Sustainable Energy Research Initiative

AERI 2011

Prof. David Cahen

Scientific Director

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Executive summary

Prof. David Cahen, Scientific Director

The Alternative and sustainable Energy Research Initiative (AERI) and the Mary and Tom Beck-Canadian Center for Alternative Energy Research serve as the framework for accelerating, coordinating, and sharing alternative energy research at the Weizmann Institute of Science. These efforts are assisted by funds provided by other far-sighted donors with a shared vision for expanding research in clean and sustainable energy. Donor-provided funds give Weizmann Institute scientists the flexibility and startup support to try out new ideas, develop new approaches, and carry out basic research that is not always funded by conventional grants.

Each November, the AERI board of directors, following recommendations of its scientific advisors, chooses which proposals to accept, and which projects will receive continued funding. Here are the new and on-going projects given grants for the 2011-2012 budget year.

Ongoing projects

Biofuels

The AERI Biofuel Consortium (ABC) was formed to build upon ongoing research efforts in plant sciences, basic photosynthesis, algal science, metabolic engineering, biological cellulose degradation and other approaches of interest to biomass-derived fuels and to provide incentives for making these basic research efforts more directly relevant to biofuels.

The consortium aims to develop new approaches for efficient biofuel production from renewable sources that do not compete with food production. Now in their second year of AERI funding, the twelve teams of scientists led by Prof. Avraham Levy continue to strengthen their efforts to provide better scientific bases for extracting energy-rich biomass from a wide variety of sources. The teams are working on the challenge through a variety of approaches: screening for genetic biodiversity, metabolic and genetic engineering, and by using metabolomics platforms to analyze the components of the biomass composition and production.

The ABC projects aim ultimately at achieving ecologically sustainable biomass production, and to provide the scientific knowledge that we need for developing technology to:

- Grow biofuel feedstock without competing with food crops
- Minimize cost of breaking down plant biomass into usable, soluble sugars
- Bioengineer crops, algae and bacteria that are optimally suited for generating liquid fuel and hydrogen
- Develop yeast strains that will optimally feed on crops-derived sugars for ethanol production

They focus on both the plant(s) and on novel enzymatic systems that turn biomass into fuel — and ways to ensure that the entire process can be done sustainably. For instance, Weizmann Institute plant scientists are performing large-scale screening on the straw from wild wheat. They are looking for varieties with a cell wall structure that is more digestible by enzymes for degradation and fermentation than existing types of cultivated wheat. They then hope to transfer this trait to modern wheat strains, and to explore engineering other plants with more digestible cell walls.

Other groups are working to genetically engineer crops to be more tolerant to stress and drought than existing ones. For instance, Prof. Yuval Eshed recently discovered that altering a particular gene in a plant delays the aging of its leaves, leading to an increase in biomass production and resulting in a juvenile biomass that is easier to digest for feed and fuel production.

Based on efforts that were already supported during the first six years of AERI, scientists are concentrating attention on microalgae and cyanobacteria, looking for species and qualities suitable for biomass production in marginal water systems and with minimal nutrient resources. They are working to identify novel genes and mechanisms controlling processes associated with efficient growth and biomass production, and with lipid and oil production. These efforts are being carried out in collaboration with our bioinformatics groups and are backed with the Institute's capabilities for transcriptome analysis, large-scale gene sequencing; and in the assembly, annotation, and mapping of the genomes. Funding from AERI is also helping establish and maintain the expensive infrastructure needed for this research, including developing analytical chemistry-based tools for lipid and carbon metabolism analysis.

Buffer layers for inverted solar cells

A team led by Prof. Milko van der Boom is working on a strategy to create low cost solar cells consisting of organic materials. The proof-of-principle of such devices has already been demonstrated. However, the inert processing conditions and limited efficiency of these types of cells hamper its commercialization. His approach is to use self-propagating assemblies as buffer layers for inverted solar cells. He hopes to demonstrate an organic solar cell that can be processed in air and has a power conversion efficiency and life-time, comparable to or better than the current state-of-the-art for small molecule-based systems. This project, parts of which are in collaboration with other Weizmann scientists, is in its third year of AERI funding.

New projects

New directions in solar cells

In order to achieve commercial applications, the efficiencies of organic solar cells that can convert solar light into electricity still have to be improved significantly. Profs. Michael Bendikov, Leeor Kronik and Gary Hodes are joining research efforts of AERI director Cahen, to explore experimentally the basic performance limitations of the new molecule-based solar cells, which are viewed as part of cheap wide-spread future solar-to electrical energy conversion. The idea behind this effort is that significant improvement in this area will come from better basic knowledge and understanding what are physical and chemical limitations to such cells. The aim is to understand the basic electrical interactions occurring at the interfaces between layers of the solar cell device and to use this understanding for defining and overcoming performance limitations on molecular solar cells.

Compact solar concentrators

Concentrating solar radiation can dramatically reduce the required area (and thus the cost) of solar cells (by replacing them with cheaper optical elements) for electrical power. While reflecting parabolic mirrors are probably the most common solar concentrators, they perform far below the so-called thermodynamic limit of maximal allowed concentration. More advanced solar concentrators, can approach the thermodynamic concentration limit, but typically do not directly concentrate the solar radiation and require an initial concentration stage to be reasonably compact. Prof. Nir Davidson is leading an effort, based on extensive studies of past optical concentrators, to find ways to concentrate the direct as well as the indirect (diffuse) solar radiation. He hopes to suggest new possibilities to enable efficient, non-tracking concentrators and reduce the need to exactly align collectors toward the sun. This could substantially reduce the costs of concentrating solar energy.

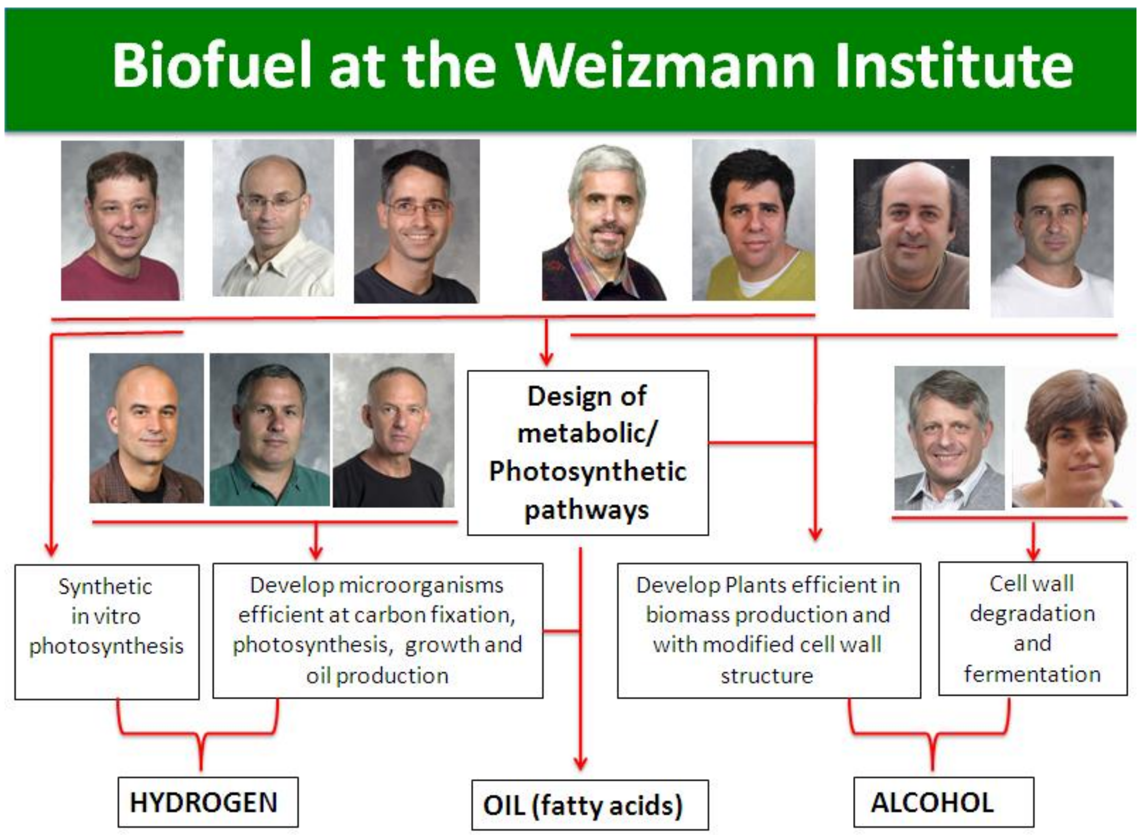
Quantum-dot solar cells

Dr. Dan Oron is leading a project to use quantum dots as the basis for a new generation of light harvesting devices. He has shown that these tiny nanocrystals of semiconducting materials can serve as light absorbers. There have been many attempts to reduce the loss of low-energy light by using advanced optical methods to "fuse" two low energy photons (i.e., quanta of light) to a single photon with a higher energy, a process called "up-conversion." However, for up-conversion to be efficient, it requires a tremendously large optical flux, typically thousands to a million times higher than that of direct sunlight. Dr. Oron envisions quantum-dot-scale devices that could use one low-energy photon to create a 'warm' electron (with insufficient energy to induce conversion to electricity) and then use the second photon to heat up the 'warm' electron. This process is quite analogous to that of photochemical conversion in the photosynthetic complex of green plants. Due to the fact that electrons can be kept 'warm' for much longer than the duration of optical excitations, the use of 'warm' electrons can lead to a significant reduction in the flux required for energy up-conversion.

Thank you for your interest in our alternative energy work and your support of the Weizmann Institute of Science's efforts to create new possibilities for our energy future. The following reports highlight scientific findings published recently by AERI-Funded projects.

Enhancing biofuels production

Twelve teams of Weizmann Institute scientists are working together on a number of basic science projects related to enhancing biofuels production. Coordinated by Prof. Avraham Levy in the Department of Plant Sciences and guided further by four distinguished emeritus professors, the groups are addressing scientific questions facing four major strategies to increase biofuels production (see chart below). The strategies are: 1) designing metabolic pathways, 2) developing plants optimized for biofuel and alcohol production, 3) advancing cell wall degradation and fermentation, and 4) developing microorganisms for biofuel production.



***Biofuels Researchers –** Top row L-R: Dr. Dror Noy, Prof. Avigdor Scherz, Dr. Ron Milo, Prof. Gad Galili, Dr. Asaph Aharoni, Prof. Avraham Levy, Prof. Yuval Eshed, Bottom row L-R: Dr. Assaf Vardi, Prof. Avihai Danon, Prof. Uri Pick, Prof. Ed Bayer, Prof. Naama Barkai.*

Designing metabolic pathways

At the genetic level, existing plants are not optimized for large-scale biofuel production. To improve their potential energy yield in a changing and limited environment requires basic and multi-disciplinary research that can integrate studies in molecular genetics, computational biology, biophysics, biochemistry, metabolism, and physiology of photosynthetic organisms. A thorough, in-depth understanding of metabolic pathways is a pre-requisite to engineer and optimize plants and microorganisms for biofuel production.

Dr. Asaph Aharoni and Prof. Gad Galili focus on direct analysis of the plant metabolism, using the plant metabolomics methods they have pioneered. Computational biologist Dr. Ron Milo works with them to look for ways to optimize several relevant metabolic processes, including carbon (CO_2) fixation, fatty acid metabolism, carbohydrate metabolism, and stimulation of the conversion of primary into secondary metabolites, such as specific alcohols.

Developing plants optimized for biofuels and alcohol

The goal of this project is to produce fast-growing plants that have a digestible cell wall. This will be done through genetic engineering, using knowledge developed by Prof. Yuval Eshed, showing that knockdown of repressors of growth creates plants with increased biomass.

Plant scientist Prof. Avraham Levy and molecular geneticist Prof. Naama Barkai are using another approach to identify hybrids or polyploids that show growth vigor and to analyze the mechanistic causes for this vigor.

Profs. Gad Galili and Ed Bayer have projects underway to re-engineer the composition of plant cell walls, usually left over as a waste product in agriculture, to facilitate its digestibility and fermentation, in particular with respect to lignin content. Prof. Galili has further plans to optimize plants for alcohol production through guiding the conversion of primary metabolism into phenolic secondary metabolites that can be further converted into biofuel-efficient alcohols.

Advancing cell wall degradation and fermentation

For the past three years, an interdisciplinary team led by Prof. Ed Bayer has pioneered the field of cellulose degradation in bacteria and the digestion of cellulose with microorganisms and enzymes. He is pursuing new directions suggested by that work, while Prof. Barkai uses the tools of computational biology and metabolomics to develop yeast strains that can produce ethanol or butanol from xylose, an abundant sugar that is one of the main components (~30%) of plant cell walls and biomass.

Prof. Bayer and his team have recently been studying xylanases that catalyze the breakdown of xylan, the second most abundant polymer on Earth after cellulose. Xylanases are commonly found in powerful multienzyme complexes called cellulosomes that are produced by anaerobic bacteria, which are considered to be among the most efficient systems for degradation of cellulosic biomass. Using their designer cellulosome approach, Prof. Bayer and his team incorporated the entire xylanolytic system of the bacterium *Thermobifida fusca* into experimental artificial cellulosome complexes and compared the combined action of these designer cellulosomes versus that of the wild-type free xylanase system. Their data demonstrated that xylanolytic designer cellulosomes displayed enhanced synergistic activities on a natural recalcitrant wheat straw substrate and could thus serve in the development of advanced systems for improved degradation of lignocellulosic material.

Recent articles

Morais S, Baraka Y,Hadarb Y, Wilson D, Shoham Y, Lamed R, and Bayer E, "Assembly of Xylanases into Designer Cellulosomes Promotes Efficient Hydrolysis of the Xylan Component of a Natural Recalcitrant Cellulosic Substrate" *mBio*, Vol 2 Number 6, November 15, 2011.

Morais S, Barak Y, Caspi J, Hadar Y, Lamed R, Shoham Y, Wilson DB, Bayer EA, "Contribution of a Xylan-Binding Module to the Degradation of a Complex Cellulosic Substrate by Designer Cellulosomes" *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*, Volume: 76, Page: 3787-3796, 2010

Morais S, Heyman A, Barak Y, Caspi J, Wilson DB, Lamed R, Shoseyov O, Bayer EA, "Enhanced cellulose degradation by nano-complexed enzymes: Synergism between a scaffold-linked exoglucanase and a free endoglucanase " *JOURNAL OF BIOTECHNOLOGY*, Volume: 147, Page: 205-211, 2010

Anbar M, Lamed R, Bayer EA, "Thermostability Enhancement of Clostridium thermocellum Cellulosomal Endoglucanase Cel8A by a Single Glycine Substitution" *CHEMCATCHEM*, Volume: 2, Page: 997-1003, 2010

Towards artificial photosynthesis

Artificial photosynthesis (AP) is at an embryonic stage. However the research we plan to conduct in biofuels will serve to advance towards artificial photosynthesis, which we expect to be a viable and thus extremely important long-term solar energy solution. Our hope is to devise a process that mimics natural photosynthesis—whereby carbon dioxide and water combine with sunlight to create energy—but will be more efficient in producing energy than natural photosynthesis, in which most energy is used for the growth, upkeep and reproduction of the organism

Artificial photosynthesis has as its goal the sustainable production of carbon-neutral sources of fuel, producing reduced forms of matter that can serve as fuel (by reacting with our atmosphere's oxygen). This sets it apart from the other renewable energy sources like hydroelectric, solar photovoltaic, geothermal, and wind which produce electricity directly, with no fuel intermediate. As such—and because the end product will be the highly concentrated, easily storable and transportable energy source that much of modern society relies on— artificial photosynthesis is a great long-term hope as source of fuel, especially for transportation. Also, unlike biomass energy, it does not require arable land, and so the concern about competing with the food supply is eliminated. Here are several projects that are underway:

Using Components of Photosynthesis

Natural photosynthesis features an elaborate system of enzymes embedded in a specialized membrane. Their cooperative action drives remarkably difficult chemical reactions that enable plants and algae to use light and water as their primary source of energy and electrons. In the process, light is captured very efficiently by two photosystems, PSI and PSII. However the ensuing biochemical reactions result in significant energy losses.

Dr. Dror Noy (left) and his lab team study the fundamental processes involved in photosynthetic solar energy conversion. Plants and evolutionarily older photosynthetic organisms use light to create energy for all their metabolic needs. They are a source of inspiration for designing artificial devices for solar energy conversion and storage. Dr. Noy's group focuses on the flow of energy and electrons to and from the catalytic sites of photosynthetic enzyme complexes. He takes a modular approach, looking at the process as a series of electro-chemical reactions between a number of catalytic beginning and ending points. The "endpoint" of each catalytic process provides the raw materials needed for the next step in the process. Their aim is to design new proteins that are capable of performing charge and energy transfers between the catalytic endpoints found in photosynthetic systems. He hopes to be able to streamline the process and make many of the steps more efficient.

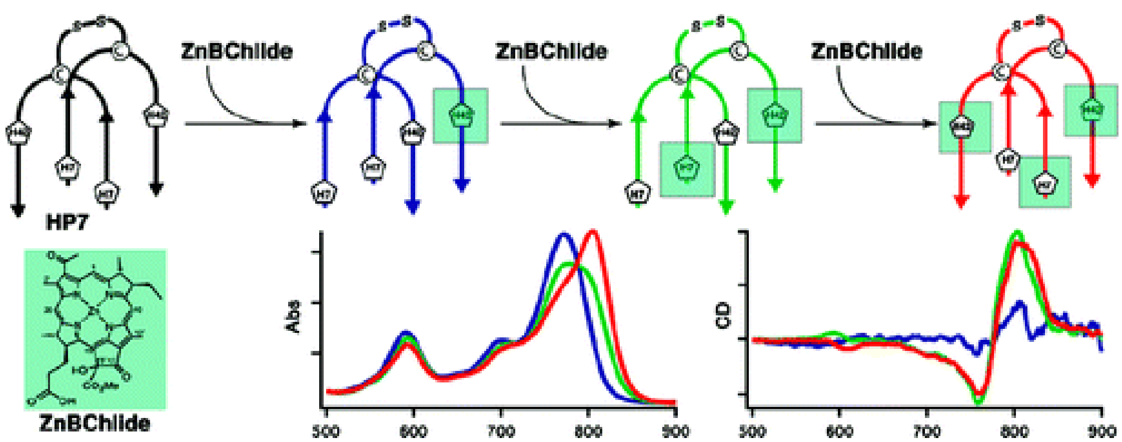
By applying state-of-the-art computational and empirical tools of protein *de novo* design, the lab constructs novel protein-cofactor complexes that simplify the natural energy and electron transfer proteins. In the next stage of the building process, they create an interface designed to couple the artificial proteins with their natural and/or catalytic partners. New designs are tested by a variety of analytical and spectroscopic methods, and the results are used for optimizing the previous designs in an iterative process.

This learning by design approach provides substantial insights into folding and assembly of protein-cofactor complexes, and the critical parameters affecting their function as energy- and electron-transfer relays. Most importantly, it can teach important lessons on how Nature achieves functional diversity by combining only a few basic modules into a variety of elaborate networks of long-distance inter- and intra-protein energy and electron-transfer reactions. In the future, these lessons may be used for designing and constructing custom-built networks of enzyme complexes to carry out chemical transformations of our choice, either in a non-biological context, or in a biological setting.

Altogether, the emerging new structures and protein design methodologies mark significant progress in their ability to develop new protein scaffolds that control and organize redox cofactors and light-harvesting pigments. Already at these early stages of design, some structures provide simplified models of natural light-harvesting and charge separation systems.

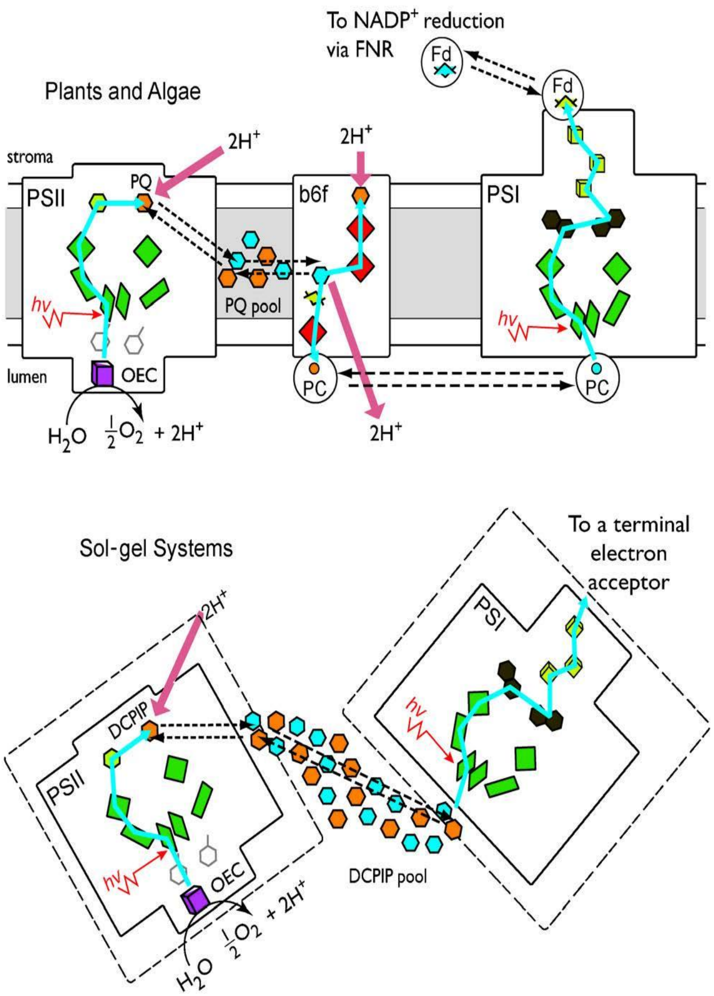
A simple model

Photosynthetic plants use interacting pairs of chlorophylls (and simple photo-active bacteria use pairs of bacteriochlorophylls) as excitation energy donors and acceptors in light harvesting complexes. Working with colleagues at the Max Planck Institute for Bioinorganic Chemistry in Bonn, Dr. Noy and his team built a pair of interacting bacteriochlorophylls on a protein scaffold. In an article in the *Journal of the American Chemical Society*, they described it as one of the simplest possible model systems to study light harvesting in action. Unlike its complicated natural analogues, this system can be constructed from the ground up, starting with the simplest functional element, increasing the complexity as needed. The illustration below shows some of the energy dynamics of their simple zinc-bacteriochlorophyllide model system.



Photosynthesis without chloroplasts

Dr. Noy and his group recently published an article in *Angewandte Chemie* which describes a potential platform for artificial photosynthesis using sol-gels (inorganic polymers based on organosilicates).



They demonstrated a simple scheme for coupling of photosystems I and II (PSI and PSII see illustration at right) in solution. This coupling enables electron flow from water photo-oxidized by PSII all the way to the reducing end of PSI. Furthermore, they showed that the same scheme can be reconstituted when both photosystems are co-encapsulated in sol–gel glasses, or even when one photosystem is encapsulated and the other is in solution. The sol–gel trapping technique is a proven method for encapsulating a wide variety of biological materials, from intact whole cells to functional individual enzymes. Their modular scheme may open new possibilities for novel reaction pathways combining biological and nonbiological elements.

Recent articles

Cohen-Ofri I, van Gastel M, Grzyb J, Brandis A, Pinkas I, Lubitz W, Noy D, "Zinc-Bacteriochlorophyllide Dimers in de Novo Designed Four-Helix Bundle Proteins. A Model System for Natural Light Energy Harvesting and Dissipation" *JOURNAL OF THE AMERICAN CHEMICAL SOCIETY*, Volume: 133, Page: 9526-9535, 2011

Braun P, Goldberg E, Negron C, von Jan M, Xu F, Nanda V, Koder RL, Noy D, "Design principles for chlorophyll-binding sites in helical proteins" *PROTEINS-STRUCTURE FUNCTION AND BIOINFORMATICS*, Volume: 79, Page: 463-476, 2011

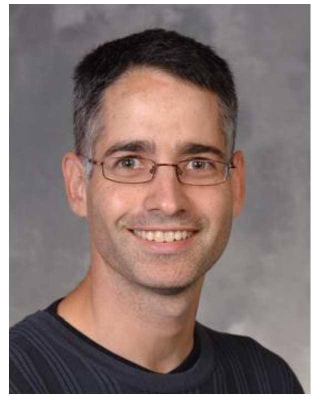
Kopnov, F, Cohen-Ofri, I and Noy, D, "Electron Transport between Photosystem II and Photosystem I Encapsulated in Sol–Gel Glasses" *ANGEWANDTE CHEMIE. Int. Ed.* 2011, 50, 12347 –12350

Cyanobacteria as new platforms for clean energy

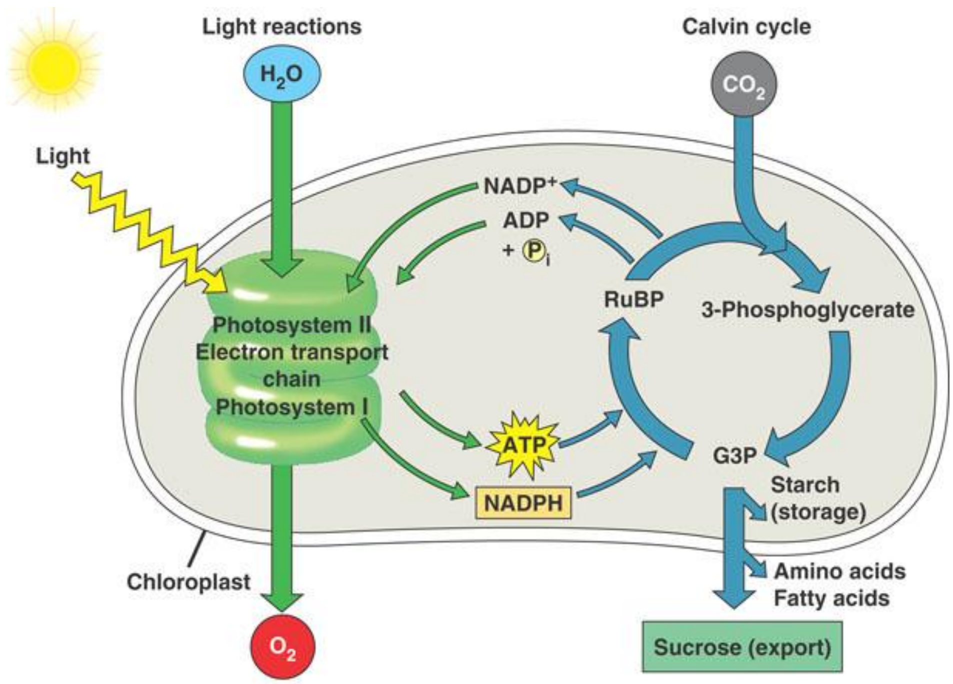
Photosynthetic bacteria and micro-algae are evolutionarily ancient organisms that have very efficient solar energy conversion (photosynthesis) machinery and some unique metabolic pathways for the production of hydrogen gas, which is considered a promising intermediate for clean fuels.

Prof. Avigdor Scherz (at right) is a pioneer in photo-dynamic therapy that uses chlorophylls from photosynthetic bacteria and laser light as a tool for cancer imaging and therapy, and for treating vision threatening diseases and other pathologies. He is collaborating with Dr. Noy to prepare mutants of promising strains of heat-tolerant cyanobacteria that have fairly simple and direct photosystem pathways. They use novel mutants, developed in the lab of Prof. Scherz, of strains of hydrogen-producing cyanobacteria and algae that are heat-tolerant and photosynthetically active over a range of 15-45°C. This could allow their bioengineered solar energy conversion systems to operate in harsh and marginal growing conditions.

Boosting Photosynthesis



Systems biologist Dr. Ron Milo (at right) is tackling issues in plant biology and photosynthesis. His research may have far-reaching ramifications for our ability to manipulate photosynthetic systems as a renewable source of energy. His group has been growing in the past year and is now numbering 13 researchers with varying backgrounds from biology to mathematics, computer science, earth sciences, and engineering. They are all united in their passion at doing basic science following their curiosity in directions that promise to bear on the challenges of sustainability. Dr. Milo and his team utilize the revolutionary tools of systems biology that enable them to rethink the basic design principles of how living things are able to transform sunlight and atmospheric carbon in a seemingly miraculous way into thousands of different and complex compounds that can make up a growing and functioning cell.



Carbon fixation is the process by which CO_2 is incorporated into organic compounds. In agriculture in which water, light, and nutrients can be abundant, carbon fixation could become a significant growth-limiting factor. Hence, increasing the fixation rate is of major importance in the road toward sustainability in food and energy production. There have been recent attempts to improve the rate and specificity of Rubisco, the carboxylating enzyme operating in the Calvin–Benson cycle (RuBP in the diagram above); however, they have achieved only limited success. Nature employs several alternative carbon fixation pathways, which prompted us to ask whether more efficient novel synthetic cycles could be devised.

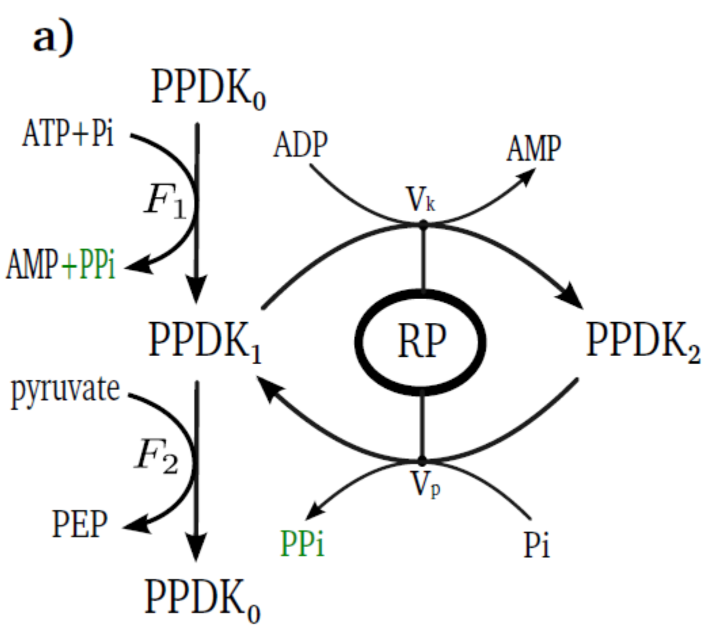
What are the limits to growth?

Last year, based on a survey of 5,000 naturally occurring enzymes and the mechanics of the six carbon fixation pathways found in nature, Dr. Milo reported that there were some promising carbon-fixing pathways that could be up to two or three times faster than the conventional Rubisco path in the familiar Calvin Benson cycle. One of the most promising used the PEP carboxylase enzyme and the "C4" carbon fixing cycle used by plants such as corn and sugarcane. These plants assimilate atmospheric CO_2 into biomass by means of the C4 carbon fixation pathway.

C4 plants use an enzymatic cycle to promote the assimilation of atmospheric CO_2 into biomass. A key step in this cycle is the conversion of pyruvate to PEP by the enzyme pyruvate orthophosphate dikinase (PPDK). The activity of PPDK, namely the rate of PEP production, is controlled by light (because PPDK needs to be correlated with the photosynthesis rate). The light level is encoded in the cell by the concentration of the enzyme ADP: high ADP means low light, and low ADP means high light. PPDK is one of the most abundant enzymes in the biosphere, constituting about 7-10% of the protein content of mesophyll cells.

Milo and colleagues asked how the PEP formation rate, a key step in the carbon fixation pathway, might work at a precise rate that is regulated by light, despite fluctuations in substrate and enzyme levels.

One of the amazing things about the C4 biological system is that the output, such as the concentration or activity of a specific protein, is perfectly insensitive to variations in the



Pyruvate, orthophosphate dikinase (PPDK0) uses ATP and Pi to produce PEP from pyruvate. It does so in two stages: first, it auto-phosphorylate itself to its active form (PPDK1). Second, it transfers the phosphoryl group to pyruvate and returns to its natural form (PPDK0). Another regulatory cycle can phosphorylate the active form PPDK1 at a different residue to form PPDK2, the inactive form of PPDK.

concentrations of all of the system's components, and yet highly responsive to the system's chief input, which is determined by the level of light reaching the plant. Such robust input-output relations are difficult to achieve. At the heart of most of these robust mechanisms are bifunctional enzymes that can catalyze two opposing reactions. The Milo group showed that PEP is just such an enzyme, and suggested that it is coupled with a product-inhibition feedback loop that couples the system output to the activity of the bifunctional regulator.

Producing proteins

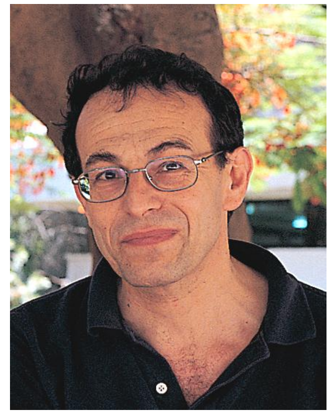
Protein levels are the dominant factor in shaping natural biological systems. Dr. Milo and his team developed a rapid and modular method to span the multi-dimensional expression space for several proteins in parallel. By combinatorially pairing genes of interest with special DNA sites called Ribosome Binding Sites they were able to modulate protein abundance by several orders of magnitude. This enabled us to produce compounds in interesting pathways to levels that broke the world record in respect to these special biosynthetic products.

In another project Dr. Milo asked what governs the concentrations of metabolites within living cells. He noted that the average enzyme is far from kinetic perfection, performing at well under maximum rates and peak efficiency. Beyond specific metabolic and enzymatic considerations, are there global trends that affect their values? He hypothesized that the many tradeoffs and conservative nature of evolution place a number of constraints on their development. His group's findings shed light on the evolution of the internal makeup of living cells and can assist in establishing coherent metabolic models that can further support synthetic biology and metabolic engineering efforts.

Finally, the Milo team has been developing an intuitive quantitative sustainability indicator utilizing a time metric to measure the environmental costs of various items. Sustainability indicators are an important emerging field, which aims to solidify the concepts of sustainability through quantification and measurements. In this study they introduced EcoTime as a sustainability indicator that uses a time metric to convey environmental burdens (i.e. resource consumption). Comparing the resource consumption of an activity or product to a benchmark quota results in the effective time cost. For example, we compare a vegetarian and animal-based meal with a similar caloric value in respect to three different resources, greenhouse gas (GHG) emissions, water and land usage. EcoTime can serve as "environmental calories" providing a gauge to daily consumption activities, and we believe can be a useful tool in the challenging path towards higher sustainability.

Converting light more efficiently

Solar energy is so attractive that we often overlook its problems. One of these is that, except for conversion to heat, the more interesting, promising, and sophisticated uses of sunlight require its direct use, and such conversion is woefully inefficient because of basic scientific limitations. While we cannot change those, we can try to circumvent them.



Prof. David Cahen

Dr. Dan Oron

Prof. David Cahn and Dr. Dan Oron are working on a joint project that aims at minimizing some of the losses inherent in the basic science of the solar energy conversion process. The most basic limits result from the fact that the light-to-electrical or light-to-chemical energy conversion is a threshold process. If the threshold is, say, in the red-light part of the solar spectrum, all infrared solar radiation cannot be used, as its energy is below the threshold. At the same time, only the red-energy part of light that is above the threshold can be used (e.g., only about half of the blue light energy would be utilized).

Research Goal

The scientists are developing an approach to decrease this loss significantly in a simple, easy to fabricate, low-cost manner by splitting the sunlight into high- and low-energy parts and guiding each part to a separate conversion system with an optimal threshold suitable for that part of the solar spectrum. Their spectral-splitting method may change the landscape of solar energy conversion for solar cells and fuels, including photosynthesis.

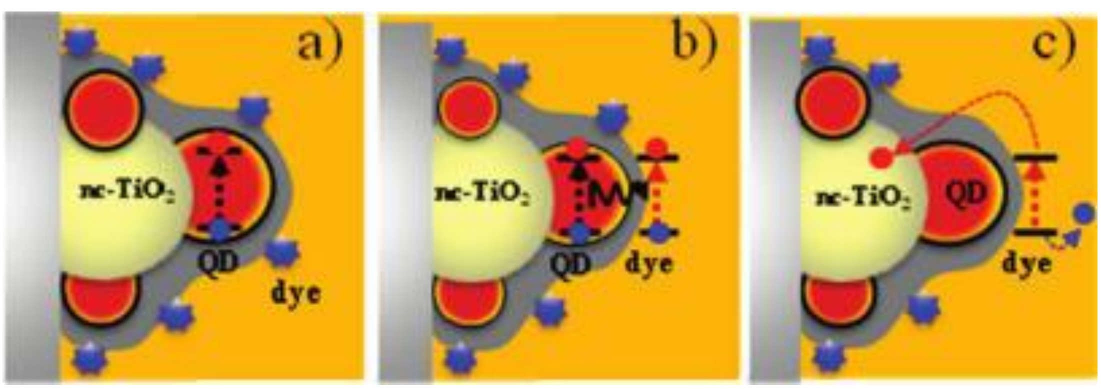
Research Progress

The team focused on the "luminescent solar concentrator" (LSC). An LSC is a piece of clear material into which are embedded the spectral splitting components, in this case so-called quantum dots—particles of nanometer size, especially suitable for spectral splitting. Combined with the proper material, the quantum dots can furthermore guide the light that falls on a large area to a much smaller area, thus also providing concentration. The concentrating part in the team's device is remarkable, as it will allow also concentrating diffuse, scattered light, something that is not possible with normal, existing commercial solar concentrators (although only for low concentrations).

Quantum dot solar cells

There has been worldwide progress in quantum dot sensitized solar cells in the last two years, with reported conversion efficiencies growing rapidly from less than 1% to values of around 4 or 5%. Dr. Dan Oron (at left) and colleagues from Bar Ilan University recently described a new way to create quantum dot (QD) solar cells that could achieve much higher conversion rates. Their new strategy is based on a phenomenon known as Förster resonant energy transfer (FRET).

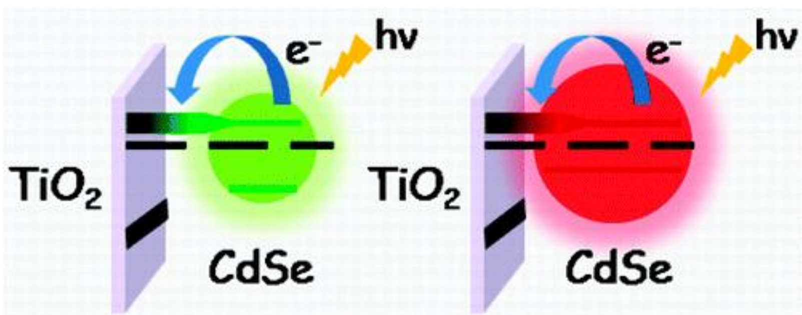
In this design, QDs serve as “antennas” (donors), funneling absorbed energy to nearby dye molecules (acceptors) via FRET rather than being used directly as sensitizers. Light is first absorbed by a donor species, which becomes excited. Before the donor can fluoresce and return to the ground state, its excitation is transferred to a nearby acceptor molecule having slightly lower excitation energy via the exchange of a virtual photon. The donor thus decays to the ground state while the acceptor is excited. The end result is that the acceptor has become excited due to an indirect process, that is, the acceptor effectively captures photons that are not directly absorbed by it (see Figure). FRET is an interesting phenomenon because it requires neither physical contact nor charge exchange. This opens up a great number of possibilities for possible donor/ acceptor pairings. This geometry can potentially reduce in a dramatic manner the required electrode thickness and opens the possibility of use of a solid electrolyte and an expected increase in open-circuit voltage.



Chain of events following QD excitation in a FRET-based QD enabled DSSC. (a) Upon illumination, the QD is excited, thus (b) transferring the energy via FRET to an adjacent dye adsorbed to the coating. (c) The dye injects an electron and is recharged by a redox electrolyte.

How do QD's work?

Understanding how quantum dot (QD)-sensitized solar cells operate requires, among other challenges, accurate determination of the offset between the lowest-unoccupied molecular orbital (LUMO) of the sensitizer quantum dot and the conduction band of the metal oxide electrode. Dr. Oron worked with Profs. Gary Hodes, David Cahen and Ron Naaman and their students to present detailed optical spectroscopy, low-energy photoelectron spectroscopy, and two-photon photoemission studies of the energetics of different sizes of cadmium / selenium (CdSe) colloidal QDs deposited on titanium oxide (TiO_2) electrodes. Their experimental findings helped answer some critical questions such as how the size of the quantum dot affects its electrical properties (size matters more than expected) and how the strength of the QD-electrode interaction allows a highly efficient QD to electrode charge transfer (see illustration below of how an incoming photon "heats up" an electron transferred from the QD to the electrode).



Recent articles

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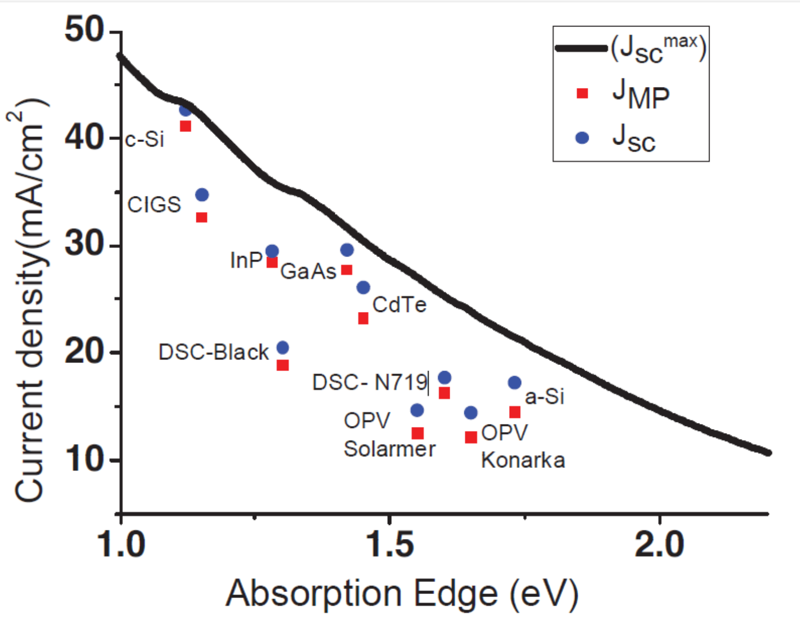
Solar cell performance

A number of Weizmann Institute groups, led by Profs. Gary Hodes and David Cahen, are working to maximize the efficiency of solar cells while exploring new ways to make them less expensive. In last year's report, we covered progress in optimizing two new types of Extremely Thin Absorber (ETA) solar cells: one based on nanoporous titanium oxide (TiO_2) made by spin coating; and another based on zinc oxide (ZnO) nanorods made by chemical bath deposition. Both of them were built on conducting glass sheets, and the researchers also published details on how to control the open circuit voltage of the cells.

Working with a very talented postdoctoral fellow from India's premier research institute, (the Tata Inst. for Fundamental Research and colleagues from Spain (University Jaume) and the USA (Princeton) Prof. David Cahen formulated criteria, based on solar cell and module performance data, that serve to evaluate and compare all types of today's solar cells. They also assessed the data to gauge how much significant progress can be expected for the various cell types and, most importantly, from both the science and technology points of view, if there are upper boundaries that could limit progress in each of these basic solar cell types. The researchers felt that the enormous efforts in photovoltaic research and development justify consideration of the existence of possible limitations. Defining such limits puts the Institute's work in a clearer framework and helps focus efforts on routes for progress in solar cell types that show the most potential for cheap, sustainable and practical energy conversion systems. The work is also meant to counter "overhype" which leads to backlashes and public disappointments which, in turn, decrease public support because of "oversell" about advances in solar energy.



Maximal possible vs. experimental photocurrents of different types of solar cells at short circuit (SC) and maximal power (MP) for best solar cells at AM 1.5.

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CO_2 to energy conversion

Prof. Igor Lubomirsky and his team recently characterized the dynamics of molten lithium carbonate (Li_2CO_3 + Li_2O) and CO_2, which is important for a number of applications ranging from carbonate fuel cells to Lithium industrial production. This expands on the chemistry of the unique system they demonstrated that captures carbon dioxide from the atmosphere and reduces it to carbon monoxide (CO)—a non-corrosive gas that can be burned directly in turbines or generators, or converted on-site into liquid fuel. It offers an attractive alternative for capturing CO_2 from the flue gas of power stations. Although it is toxic in high concentrations, CO has been used for over 100 years as an intermediate chemical product.

Prof. Lubomirsky invented a system that allows continuous reduction of CO_2 to CO in molten Li_2CO_3 at 900°C with a thermodynamic efficiency above 85%. The technique does not use precious metals or toxic chemicals, nor does it emit toxic by-products. However, electrolysis in molten carbonates (like lithium carbonate) required finding solutions to serious material stability problems. In a recent study published in the *Journal of Chemical Thermodynamics*, he was able to show, both theoretically and experimentally, a range of temperatures and concentrations of Li_2O in the Li_2CO_3 melt that are in equilibrium with atmospheric CO2 or are capable of absorbing CO_2 from air.

Photo of the testing apparatus for conversion of CO_2 to CO by electrolysis of molten Li_2CO_3. The setup is similar to a large, hot battery. Inside a special cell, a chemical compound is heated to around 900°C, and an electric current is passed through the compound. When CO_2 is continuously fed into the cell, the result is pure CO and oxygen.

Recent articles

Kaplan V, Wachtel E, Lubomirsky I, "Conditions of stability for $(Li_{(2)}CO_{(3)} + Li_{(2)}O)$ melts in air" *JOURNAL OF CHEMICAL THERMODYNAMICS*, Volume: 43, Page: 1623-1627, 2011

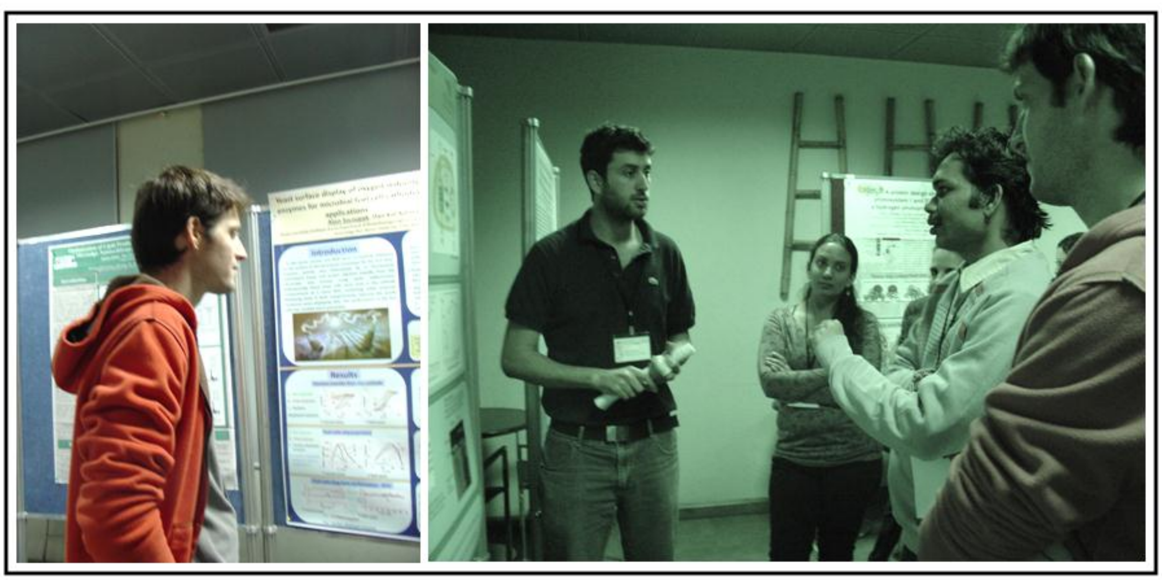
Kaplan V, Wachtel E, Gartsman K, Feldman Y, Lubomirsky I, "Conversion of CO_2 to CO by Electrolysis of Molten Lithium Carbonate" *JOURNAL OF THE ELECTROCHEMICAL SOCIETY*, Volume: 157, Page: B552-B556, 2010

Biology for Renewable Energy student workshop

The Biology for Renewable Energy Workshop (BREW) held 6-9 December, 2011 was aimed at students and postdocs involved in the research of renewable fuels of biological origin. The student-oriented convention provided an informal forum for sharing information among members and discussing the latest development and current challenges in the field. The program featured keynote lectures by leading experts from both academia and industry, but the main emphasis was on students presenting their own work. The main themes addressed were:

- Bioethanol and biodiesel production
- Degradation of ligno-cellulosic waste
- Hydrogen evolution by biological systems
- Artificial photosynthesis
- Ethical, ecological and economic considerations of large scale usage of biofuels.
- Energy policy.

The workshop, held at the scenic Ramot Hotel in the Golan Heights, was sponsored by the AERI and the Maurice and Gabriela Goldschlager Conference Foundation at the Weizmann Institute, the Grand Technion Energy Program, Ormat, Israel Cleantech Ventures, Eilat Renewable Energy, the Israel National Infrastructure Office, Agriculture and Biotechnology of Drylands, and FuturaGene.



Above: Students at a poster session

Thanks

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