Welcome CAP Executive Board

February 5, 2009

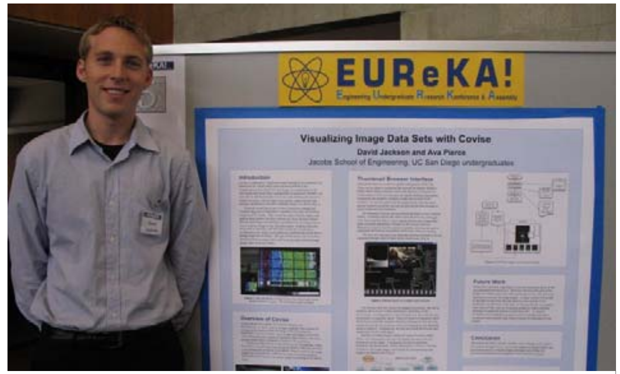
CAP 2008 - 2009 Leadership

CAP Chairman:
Rich Goldberg
VP, Corporate Quality, Cisco

CAP Vice Chairman:
Danny Brown
VP, Technology Development, Cymer

EUReKA! a new CAP benefit

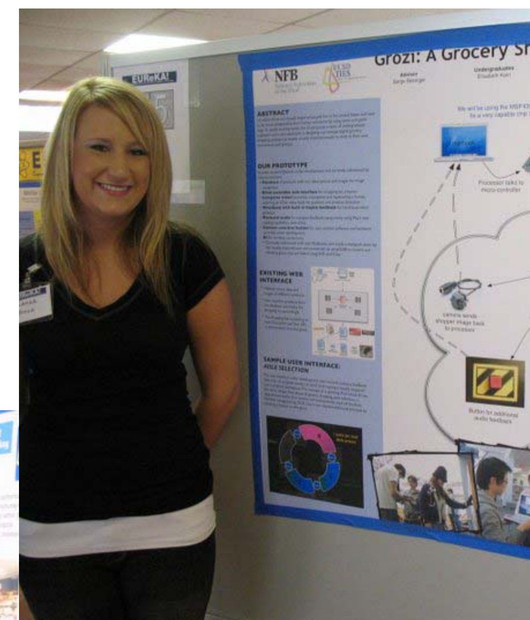
Engineering Undergraduate Research Konference and Assembly



EUReKA

UC San Diego
Jacobs School of Engineering

Engineering Undergraduate Research Konference & Assembly



Welcome Distinguished Students

Jacobs School Scholars and Fellows

T E S C
Triton Engineering Student Council
UCSD Jacobs

SWE uc san diego
society of women engineers

UCSD TIES
Teams In Engineering Service

Triton Engineering Student Council

Sara Richardson

TESC President, BioEng '10

serichardson@ucsd.edu

tesc.ucsd.edu/eweek

UCSD Jacobs | TESC Triton Engineering Student Council

Triton Engineering Student Council

NSBE

Society of Hispanic Professional Engineers

ΦΣΡ san diego

SPIE

ASME

AIChE UCSD

UCSD BMES

SCSE UC San Diego ASCE / SEAOSD

ETA KAPPA NU

SWE uc san diego society of women engineers

IEEE

SAE

SAGE

TAU BETA PI
CALIFORNIA PSI - THE ENGINEERING HONOR SOCIETY

I·A·E·S·T·E

cses

AIAA @ucsd
American Institute of Aeronautics and Astronautics

UCSD Jacobs | T E S C
Triton Engineering Student Council

{E-g(a)me s}

"It's like the Olympics, but for Engineers"

3rd Annual, Tuesday, February 17, 2009

- **This Year: WALL·E-Games**
- **3 Astronomical Competitions**
  - **Rover Ride**
  - **Rocket Launch**
  - **Lunar Landing**
- **18 Engineering Orgs & Free BBQ**
- **Fun Booths for Spectators!**

UCSD Jacobs | TESC Triton Engineering Student Council

ENSPIRE

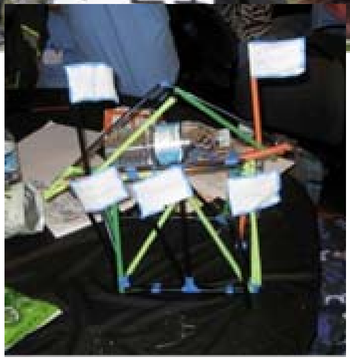
INTRODUCING ENGINEERING FUTURES TO OUR YOUTH

2nd Annual, Wednesday, February 18, 2009

Sponsored By:

SPAWAR Systems Center San Diego

- 400 Middle School Students
- 100 UCSD Volunteers
- Lab & Campus Tours, Experiment / Demonstration Tables, Design Competition
- Take-Home Bags filled with engineering goodies



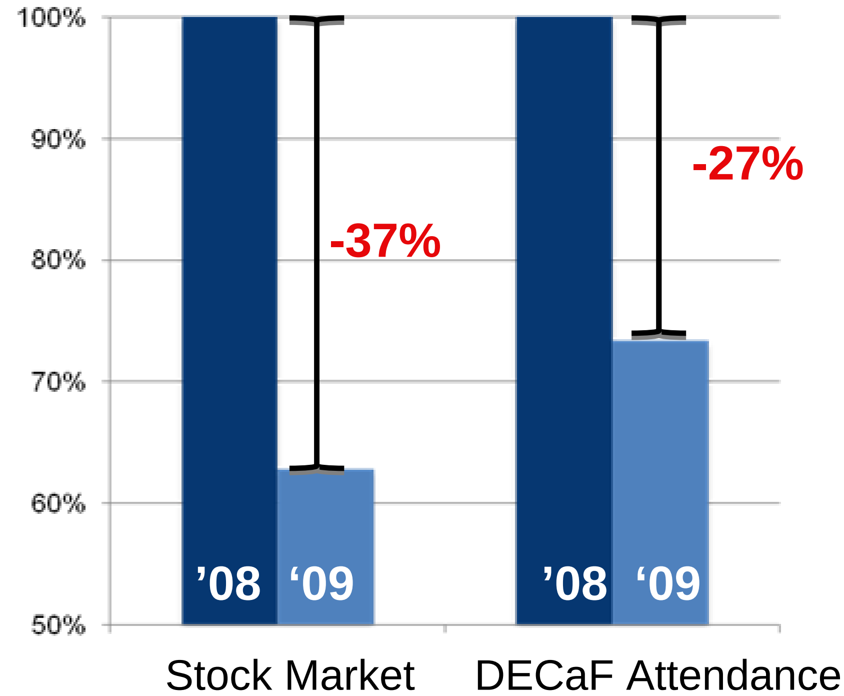
UCSD Jacobs | TESC Triton Engineering Student Council

DECaF

Disciplines of Engineering Career Fair

12th Annual, Friday, February 20, 2009

- **Over 70 Companies for 3 Consecutive Years!**
- New Joint-Sponsorship option with Research Expo
- 6 Corporate Sponsors
- Updated Functionality of Resume CDs
- Pre-DECaF Workshops: Resume Marathon,
  How to Approach a Recruiter, 1st Impressions
- CAP Café in the Ballroom
- Recruiter-Volunteer Mixer following the fair
- **Registration open until Friday for CAP Companies**



CYMER ViaSat SAIC From Science to Solutions QUALCOMM NAVY BD BD Biosciences

SOCIETY OF WOMEN ENGINEERS

University of California, San Diego
Stephany Chang, BioEng ‘09
stchang@ucsd.edu
http://swe.ucsd.edu

2008-2009 goals

We know the most valuable engineer in the workplace is a well-rounded, resourceful one. The Society of Women Engineers (SWE) plays an important role in the development of such an engineer. We provide many activities and events to aid our members in achieving these goals.

- Professional Development
- Building Community

Industry

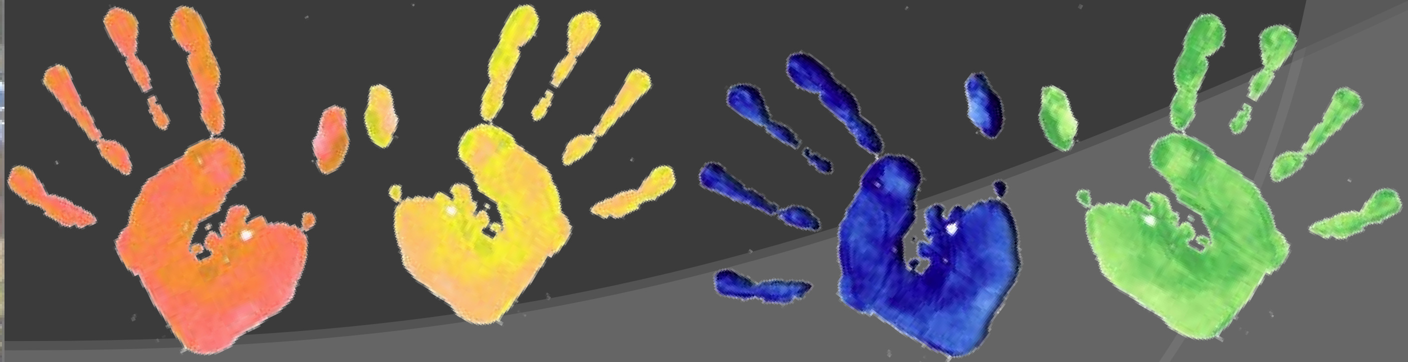
To provide our members with great networking tools by building a closer relationship with Industry

- Evening with Industry
- Mocktail
- Industry Events
  - Industry Tours
  - Company Presentations
  - Networking Workshops

Outreach

To inspire members of the community to become curious and innovative thinkers

- Weekly outreach at Spreckels Elementary
- SD Science Festival
- Girl's Day Out



Teams In Engineering Service

Dr. Mandy Bratton
Hourieh Fakourfar EE ‘09
Nick Nolta BioEng ‘10
Alisha Roger EE ‘11
on behalf of the TIES Program

Making A Difference

- Faculty-advised, multi-disciplinary teams
- Long-term projects
- Building dreams for non-profit organizations and their clients

What Kind of Professional Does TIES Create?

- Real clients
- Real deliverables
- Leadership skills
- Communication skills
- Diverse, multidisciplinary teams
- Budget management
- Appreciation for the positive impact technology and engineering can have on social conditions

Reaching Farther - Global TIES

- New Initiative
- Working with NGOs to solve problems where needs are the greatest
- Students develop global competence and leadership
- Developing programs in Kenya and Fiji

UCSD TIES
Teams In Engineering Service

Partner With Us

- Make a difference
  - Sponsor a team or internship
  - Volunteer your time and talents as a technical consultant
  - Donate equipment, software, or services
  - Make a gift of any size to the TIES Sustainability Fund

Welcome New CAP Members!

DIRECTV®

eset

Enterprise Informatics

KUITY

- Alan Kiraly, Chief Executive Officer

Enterprise Informatics

- Enterprise Information Management software
- 25 years+, 250+ customers, > 60,000 users
- Offices in San Diego, London and Stellenbosch
- Key customer markets: Energy, Construction, Transportation, Government

NuStart Energy
AkerSolutions
Constellation Energy
Network Rail
South African Airways
City of Las Vegas Nevada
GE
Bechtel
Cubic
Sempra Energy
BT
Entergy
CH2MHILL

eB Product Description

- Enterprise Information Management
  - Model & Classify Information Assets
  - Configuration/Change Management
  - Records Management
- Cost effective Microsoft technologies
  - Vista and Windows Server 2008 certified
  - .NET
  - MS SharePoint

Microsoft GOLD CERTIFIED Partner

CERTIFIED FOR Windows Server 2008

CERTIFIED FOR Windows Vista

Partnering with Jacobs

- Mentoring energetic, intellectually curious students
- Seeking talent for a great team
- Explore opportunities for product in curriculum
- Potential synergies with other San Diego companies

Enterprise
Informatics

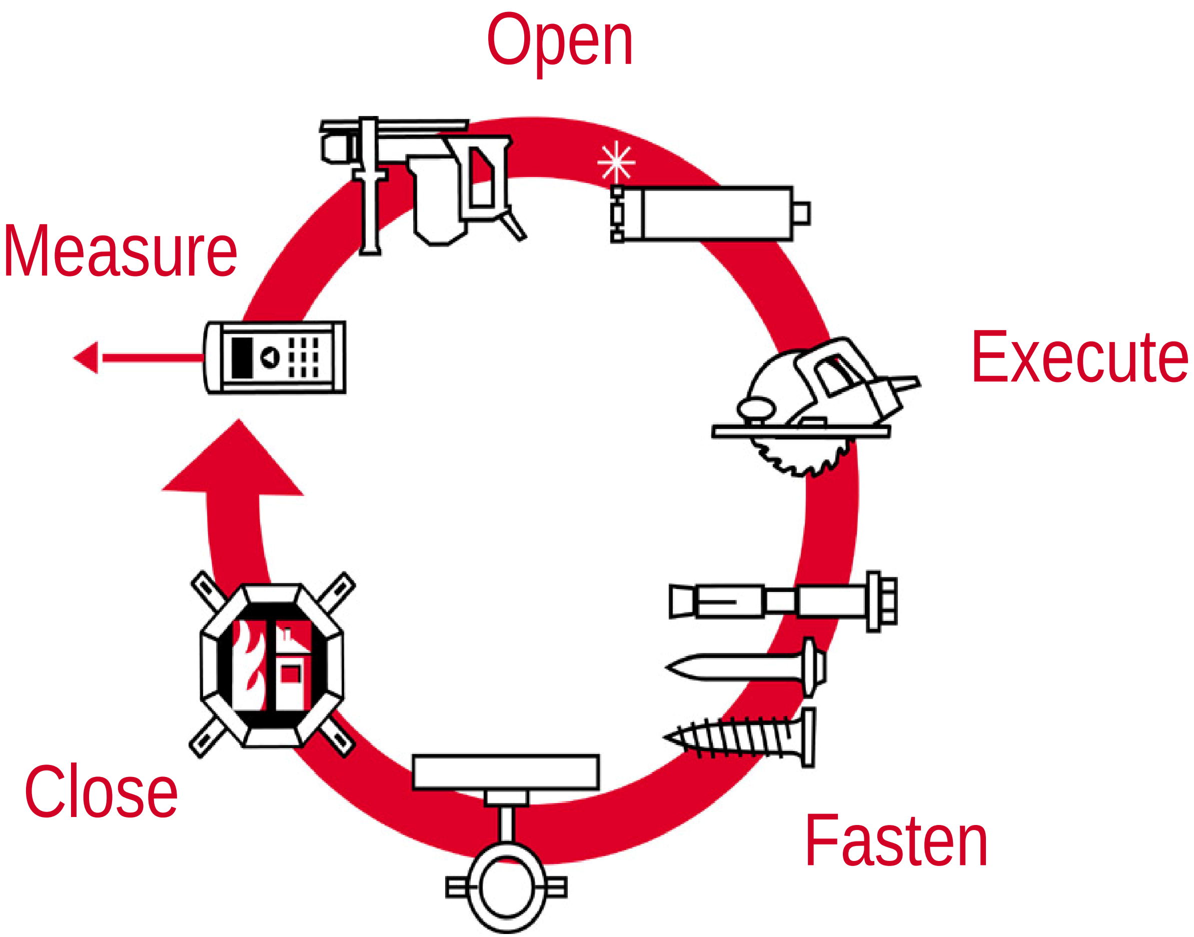
Matthew Hoehler
Director of Research

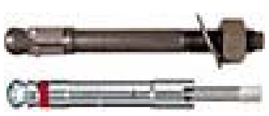
Hilti North America

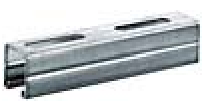
HILTI Company Background

- **HILTI develops global solutions for the international construction industry**
- **HQ in Schaan in the Principality of Liechtenstein**
- **20,000 employees, 120+ countries around the world**
- **200,000 customer contacts every day**
- **“Hilti. Outperform. Outlast.”**

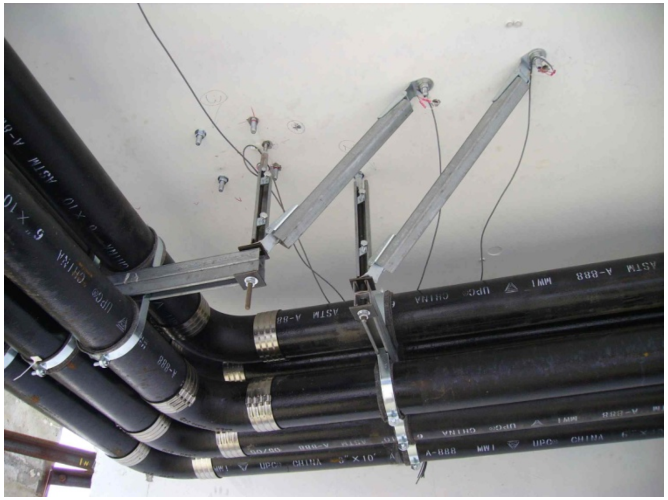
Hilti Products: System solutions







Collaboration with UCSD on basic research



HILTI involvement in TEAM internships

<u>2006</u>

Battery-powered adhesive dispenser

<u>2007</u>

Concept and usability studies for anchor product Instructions for Use

<u>2008</u>

PROFIS anchor software GUI

High-voltage plug for mining drill

Partnership with the Jacobs School

- Explore the areas of research that are import to Hilti as an international technology leader in the construction industry. The Jacobs School truly embraces and understands “Global Impact”, the heart of our business.

- Source of highly capable talent, the future of Engineering

- Explore opportunities for product in curriculum

Dean's Report:
Jacobs School of Engineering
Dean Frieder Seible

We are not untouched by the economic downturn

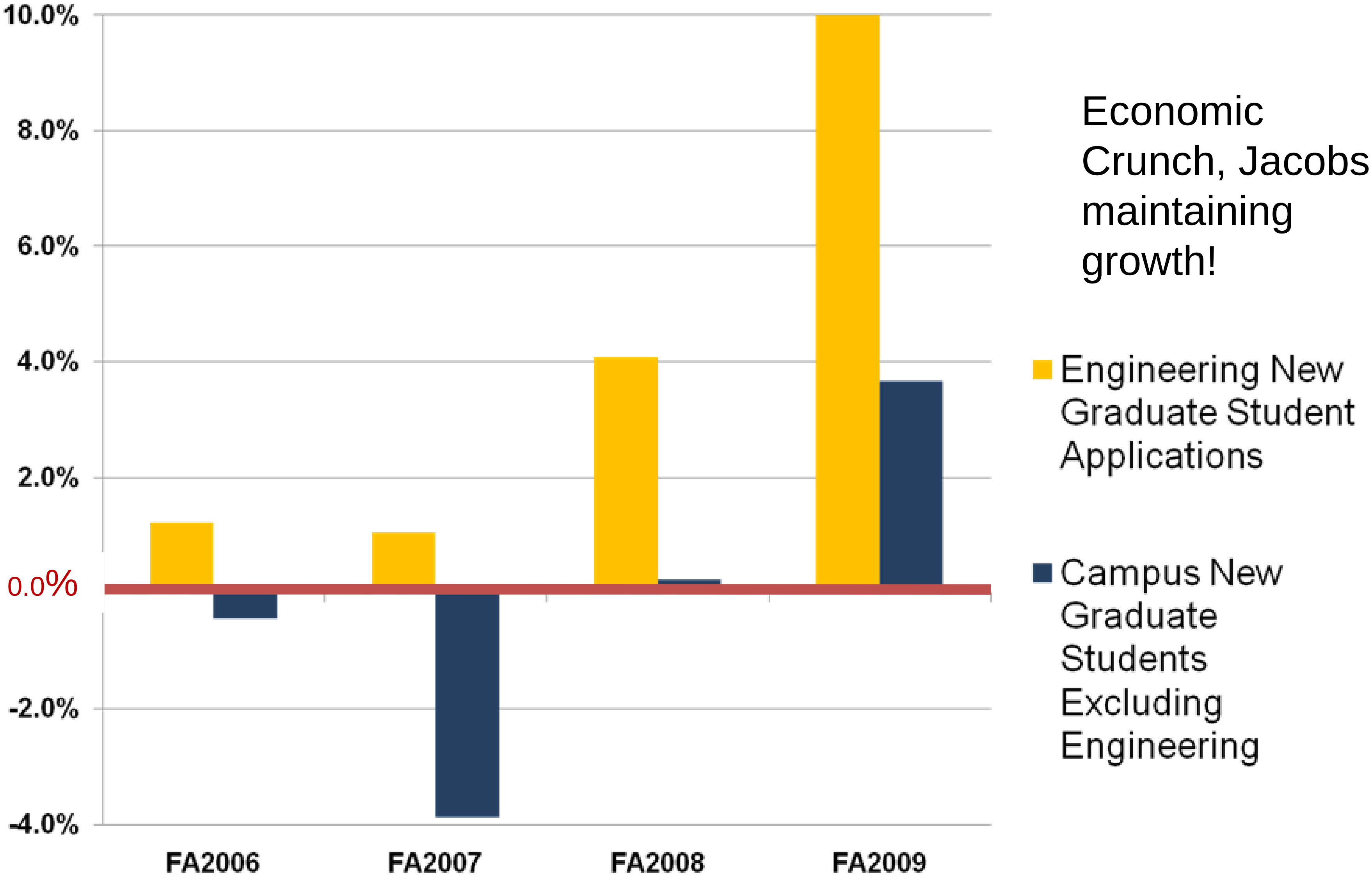
“The Engineering Neighborhood”

BUT…relationships and reputation can weather the storm

- **Applications are up**
- **Still hiring top faculty**
- **Innovations survive tough times**
- **Internships are ideal and…**

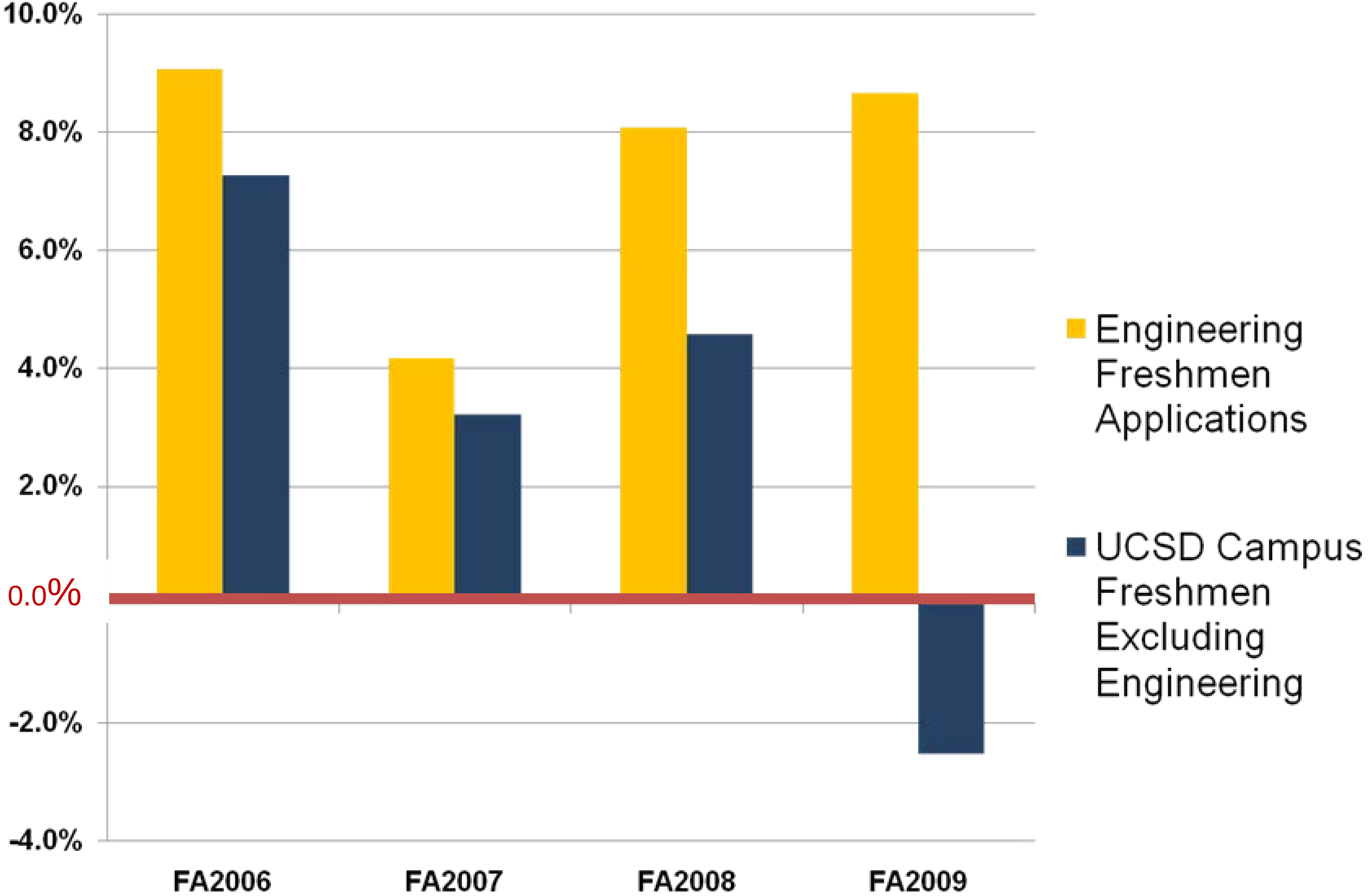
We value our community built on excellence, innovation and leadership above all else so stay the course with us.

Growth in Graduate Program Applications



Economic Crunch, Jacobs maintaining growth!

Growth in Undergraduate Program Applications



Faculty Recruitments 2009 still going strong!

Bioengineering (BE): 2

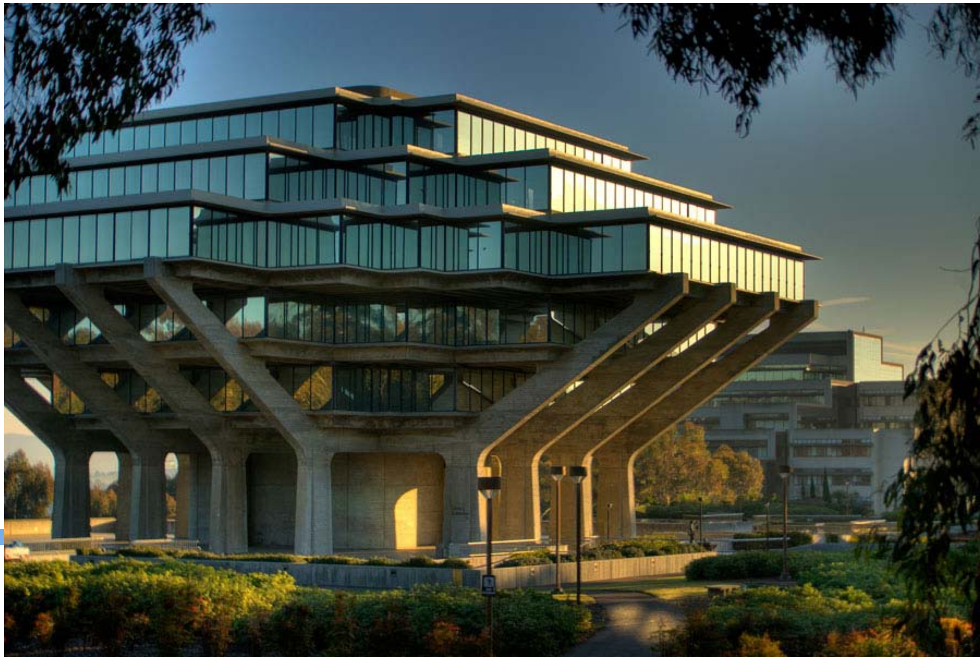
Computer Science & Engineering (CSE): 2

Electrical & Computer Engineering (ECE): 2

Mechanical & Aerospace Engineering (MAE): 4

NanoEngineering (NE): 4

Structural Engineering (SE): 2

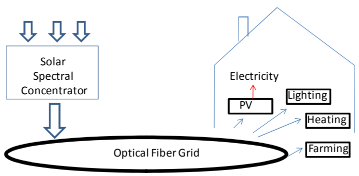


UCSD Jacobs | Corporate Affiliates Program

Von Liebig Center

2008 San Diego Clean Tech Innovation Challenge Awards

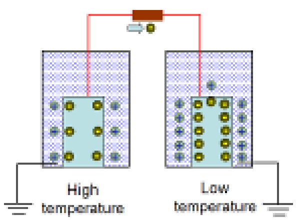
Thursday, Oct. 30 5:00 pm.-8:00 p.m.



Paul Yu, electrical engineering, UCSD

Solar Spectral Concentrator

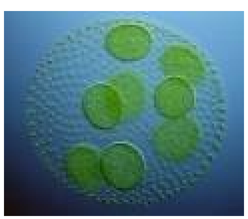
Alternative approach to conventional photovoltaics in which light is transported through optical fiber



Yu Qiao, structural engineering, UCSD

High Efficiency Thermal Harvesting Materials

Converts waste heat to generate electricity using nonporous material



John Love, chemistry/biochemistry, SDSU

Efficient Extraction of Biodiesel from Algae Cell Membranes

Enzyme which extracts oil from algae to be converted to biodiesel

UCSD Jacobs
VON LIEBIG CENTER
FOR ENTREPRENEURISM AND TECHNOLOGY ADVANCEMENT

QUALCOMM INCORPORATED

THE CITY OF SAN DIEGO
ECONOMIC DEVELOPMENT
CLEANTECH INITIATIVE

Novel Solar Energy Collection, Transmission, and Conversion

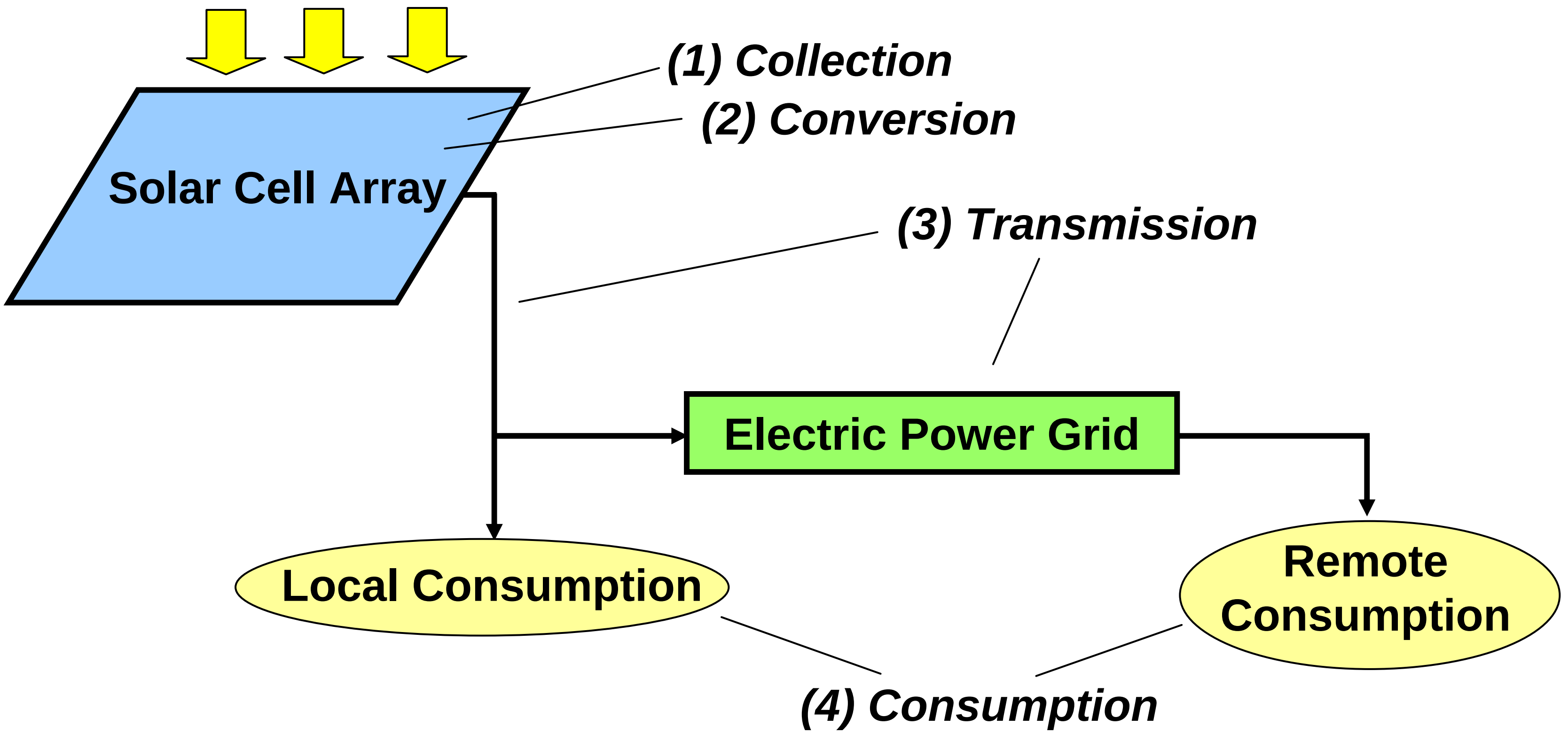
Dr. Paul Yu

Department of Electrical and Computer Engineering

Jacobs School of Engineering

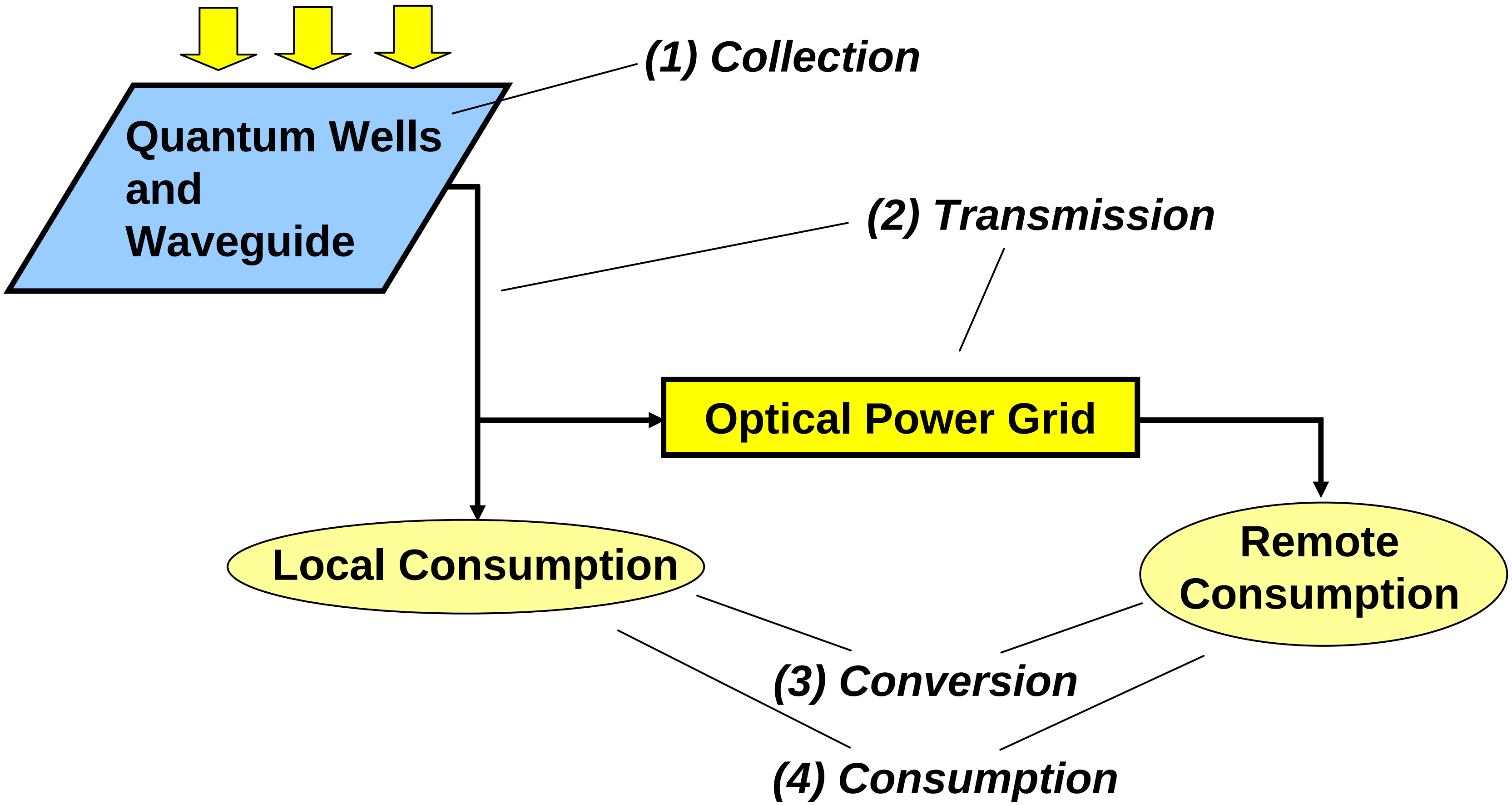
University of California, San Diego

Conventional Photovoltaic Systems



In conventional photovoltaic systems, most of the sun’s energy ends up as heat loss right at the collection/conversion point.

A New Approach



A New Use of Solar Energy

- *Collection*: Quantum Wells offer a more efficient collection mechanism because
  - Higher solar spectral coverage
  - Not sensitive to direction of incoming photons
  - Photons are efficiently guided and swept into the optical fiber
- *Transmission*: Wideband transmission of photonic energy over optical fiber can be more efficient than transmission of electrical energy because photons do not interact with each other.
- *Conversion*: Adds flexibility in how and where to convert photonic energy, based on end use (light, heat, electricity), leading to more efficient conversion.

Harvesting Electricity from Thermal Energy

Dr. Yu Qiao

Department of Structural Engineering

Jacobs School of Engineering

University of California, San Diego

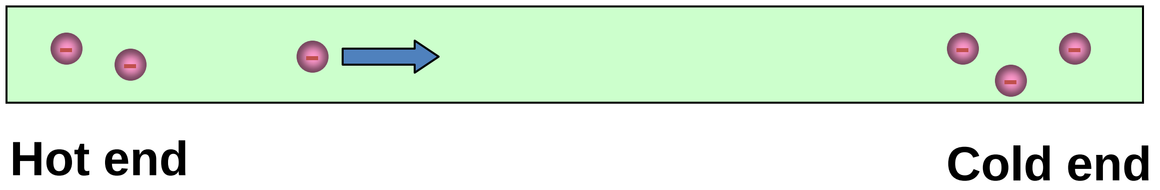
Current Technology

Conventional thermoelectric technique: Seebeck effect – electron diffusion from hot regions to cold regions of a conductor/semiconductor

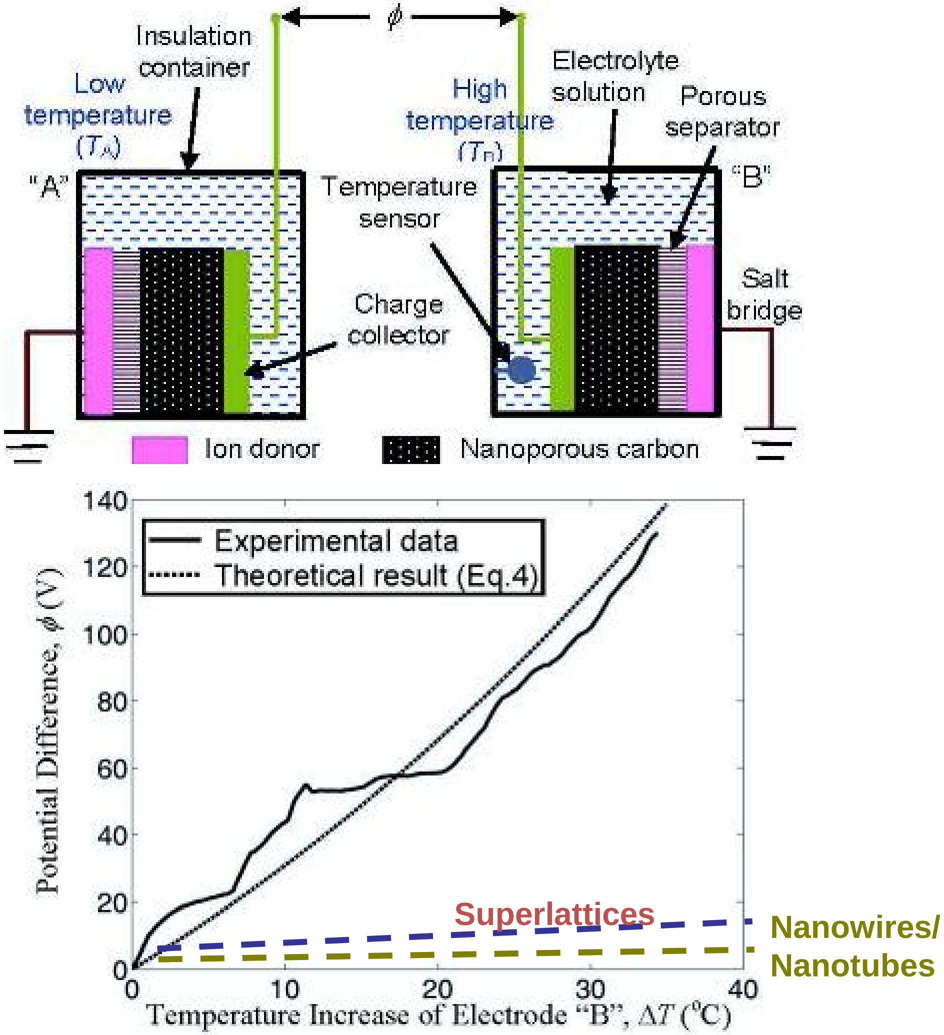
Problems:

Low conversion efficiency (5-10% of Carnot limit) due to thermal shorting – energy lost through direct conduction

Low power density (< 1/2 watt/kg)



Using Nanoporous Electrode to Amplify the Ion Adsorption Effect



1. If a nanoporous material is used, the electrode surface area can be ultrahigh (2000 m^2 per gram), without increasing system mass and volume.
2. A nanoporous material is a solid that contains a large volume fraction (30-90%) of nanometer-sized pores.
3. Preliminary experimental results have demonstrated high power density (~100 W/Kg) and high energy conversion efficiency (> 90% of Carnot limit)

UC San Diego: A living laboratory for energy conservation and alternative energy solutions

Community of 40,000 with all aspects of urban life

Photovoltaics: 1 MW Installed
2.4 MW planned for 2009

Smart Grid: monitor microclimate to adjust HVAC and irrigation in real time

Fuel Cell: 2.8 MW cell to be installed in 2009 using waste methane from water treatment plant to produce hydrogen and electricity

Wind Energy: use of off-peak wind energy for UC San Diego 24/7 operations.

Sea Water Cooling: saves $4M in energy, 400 liters of water

New Initiatives

Ingolf Krueger, Associate Professor, Computer Science & Engineering and

Director,
Bernard and Sophia Gordon Engineering Leadership Center

The Bernard and Sophia Gordon Engineering Leadership Center

UC San Diego, Jacobs School of Engineering

Overview

- Engineering Leadership
- Gordon Center Vision
- Admission and Certificates
- Education Program w/Example Syllabi
- Awards Program
- Alumni Network, Surveys and Events
- Operations
- Leadership Qualities Addressed

Engineering Leaders

- Maintain the highest level of integrity and ethics in all conduct.
- Have the vision to understand the issues facing society and how an engineering project can help address those issues.
- Have the breadth and depth of engineering knowledge to understand constraints and possibilities in developing an engineering innovation.
- Know how to assess the potential market and listen to potential users in order to look for additional opportunities for innovation.
- Have the ability to convincingly communicate their vision downward, upward and outward.

Engineering Leaders

- Know how to prepare novel product proposals and an accepted business plan.

- Take risks in exploring or inventing innovative designs and processes in order to meet challenging performance goals.

- Accept personal responsibility for developing an innovative project on time, to budget and to specification of the client.

- Understand how to recruit, motivate, educate, empower, and engender loyalty from team members.

- Possess a passion and intellectual drive for life-long learning.

Overview

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Gordon Center Vision

- Identify talented students with leadership potential through a competitive application and selection process.
- Teach the principles, theory, attitudes and skill sets required to be an engineering leader through a defined set of courses at the undergraduate, graduate and professional levels.
- Require students to practice leadership skills by managing and executing a challenge technical project on time and to the customer's satisfaction.

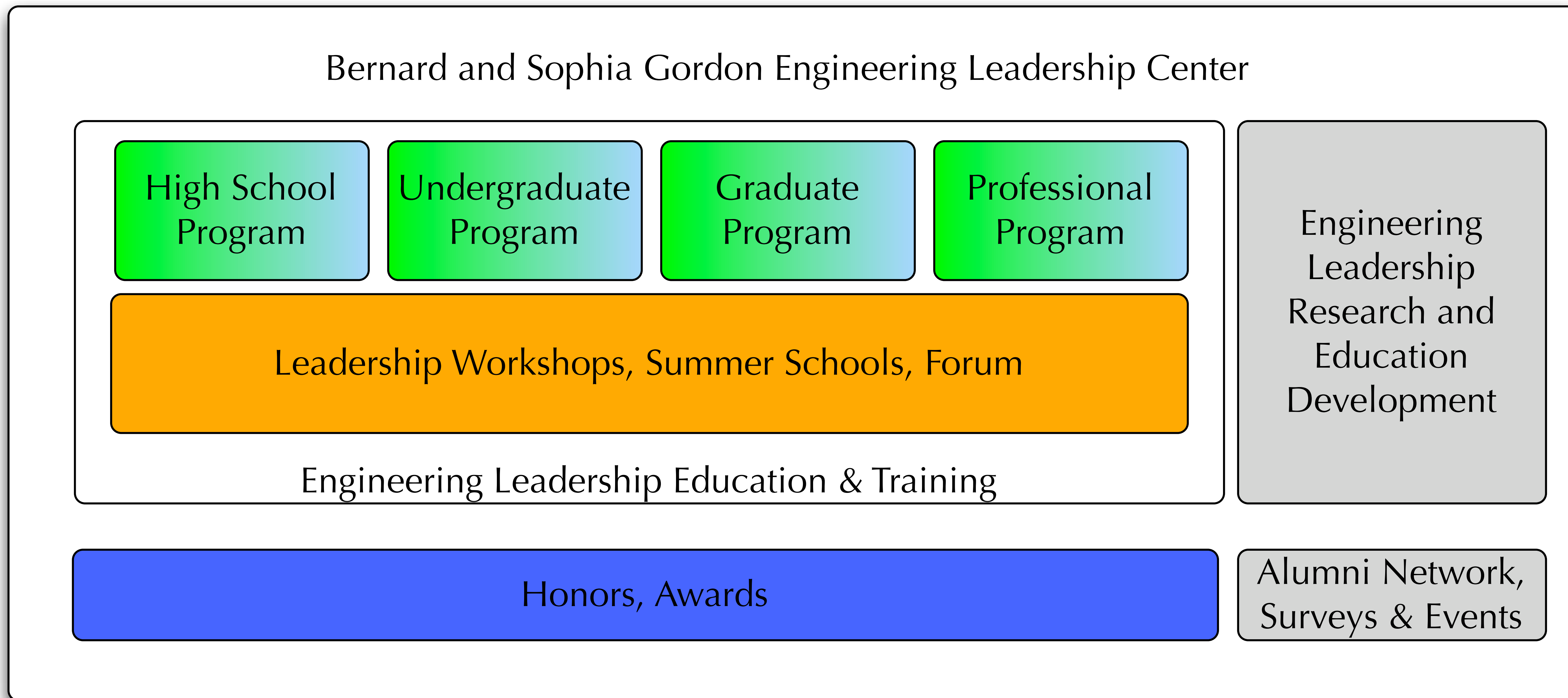
Gordon Center Vision

- Expose students to the advice, experience and attitudes of proven engineering leaders through a series of workshops, leadership forums, and summer schools.

- Reward outstanding engineering leadership through the Gordon Engineering Leadership Awards.

- Measure success of and continuously improve the Center's programs by means of surveys and tracking the progress of students and alumni.

Structure of the Gordon Center



Overview

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Admissions and Certificate

- Admit 10 students per year *each* at the undergraduate, graduate and professional levels.
- After completing the program, students will receive a Gordon Engineering Leadership Certificate and will join the Gordon Alumni Network.

Overview

- Engineering Leadership
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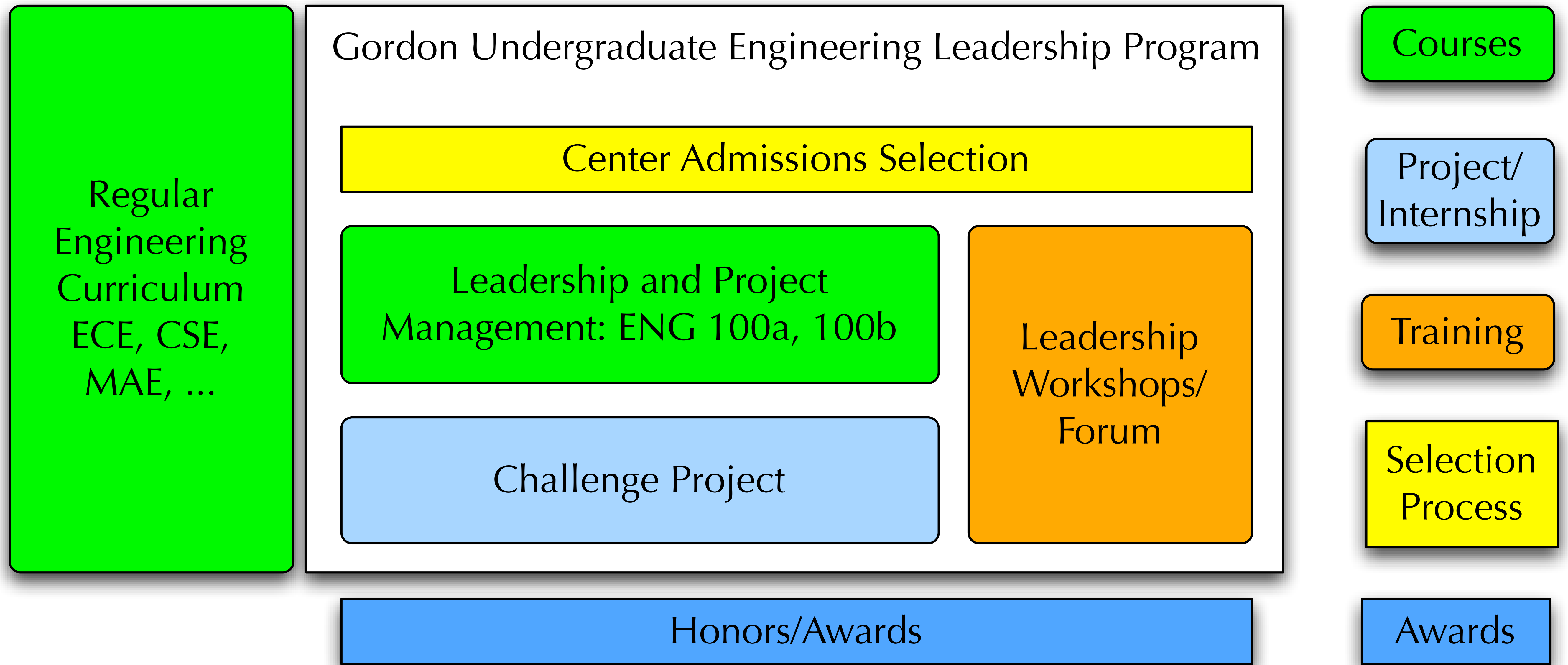
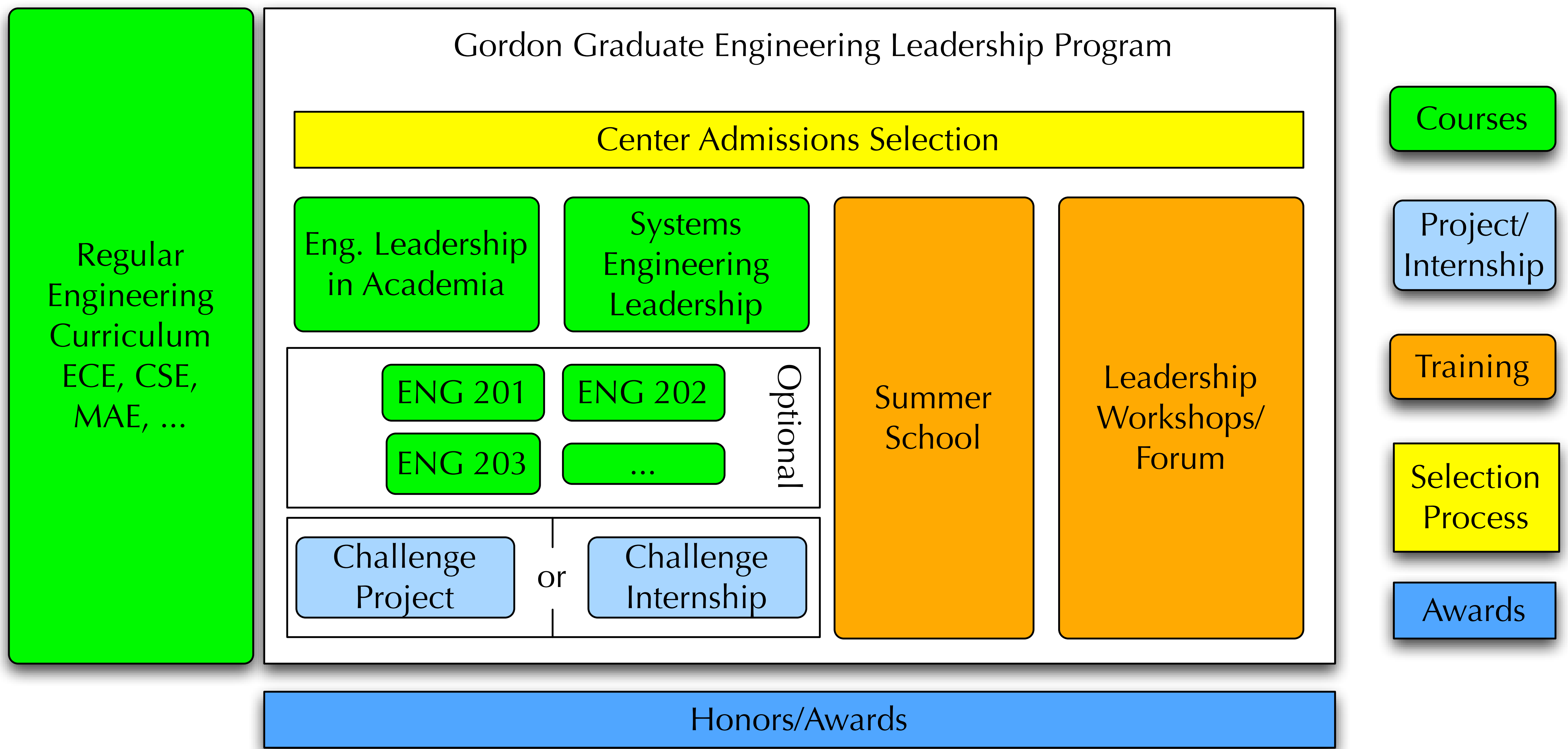
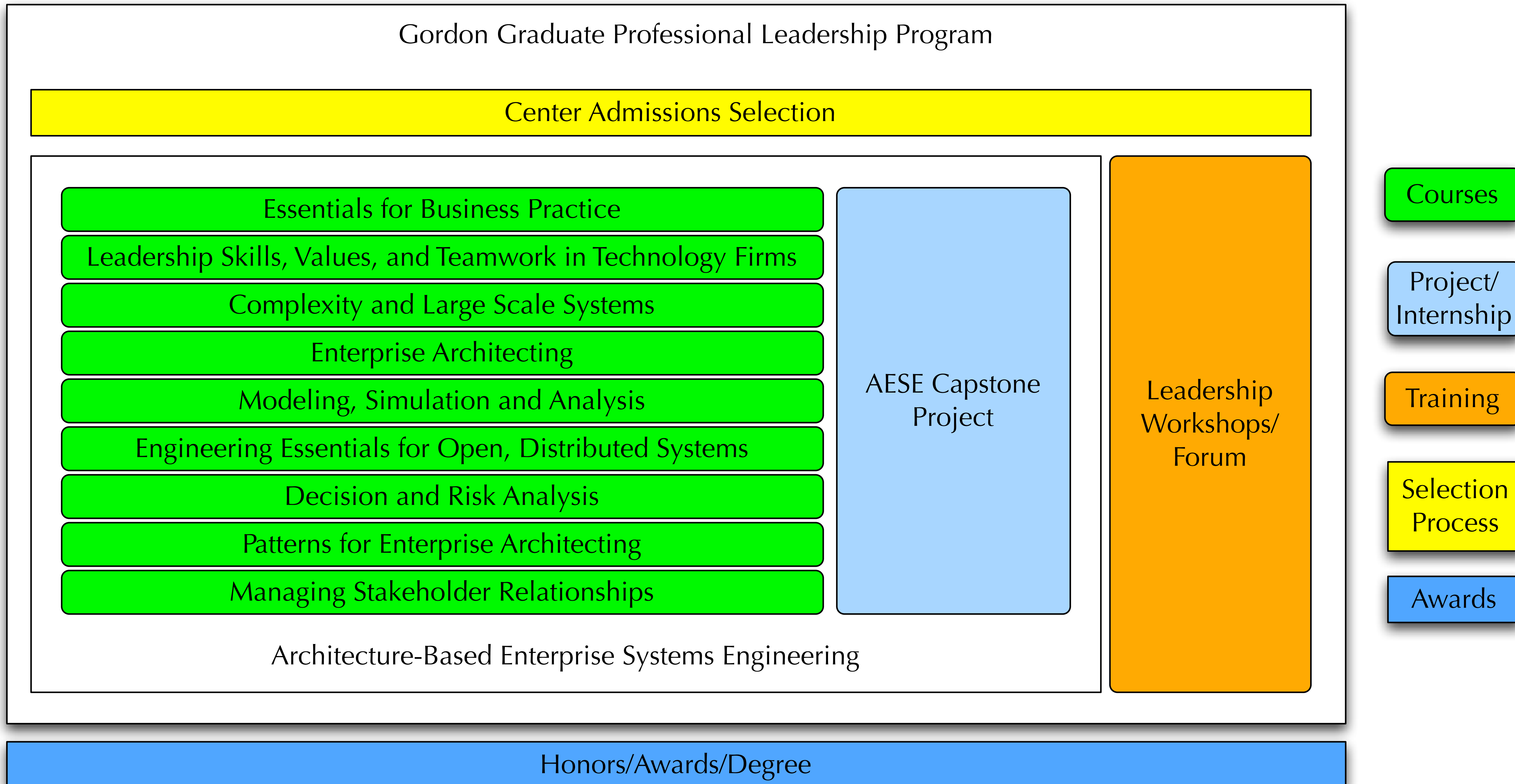
Gordon Center Undergraduate Program



Gordon Center Graduate Program



Gordon Professional Leadership Program



Overview

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Awards Program

- Goal: present annual Bernard and Sophia Gordon Engineering Leadership Awards to the most accomplished student and industrial/government/military engineering leaders.

- Award recipients will be named Gordon Fellows, and receive:
  - A Gordon Fellows Medal and Certificate
  - A prize
    - *of $500 for High school student recipients*
    - *of $2,500 for undergraduate student recipients*
    - *of $10,000 for graduate student recipients*
    - *no monetary award at professional level*
  - Membership in the Gordon Center Alumni Network.
  - Invitations to selected VIP gatherings at the Jacobs School.

Overview

- Engineering Leadership
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- Admission and Certificates
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- Leadership Qualities Addressed

Alumni Network, Surveys and Events

- Cultivate an engineering leadership community by building a Gordon Center Alumni Network.
- Connect current and former Gordon Scholars, and all of them to current engineering leaders.
- Encourage life-long learning and mentorship.
- Support performance measurement, monitoring and further center program refinement and development.
- Engage alumni via surveys and invitations to annual events

Objectives and Success Measures

- Produce alumni who are effective engineering leaders and who create new products and jobs that benefit society.

- Short-term:
  - Track student demographics that do/do not participate in leadership programs
  - Student/Client surveys on effectiveness of the programs

- Long-term:
  - Follow career paths of Center Alumni
  - Compare "time to leadership position"
  - Ask alumni to return as mentors/forum speakers

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Operations: Structure

- Center Leadership and Administration
  - Director
  - Managing Director
  - Support Staff Member
- Reports
  - Annual Mid-Year
  - Full Annual
  - First year: iterative refinement with constant communication
- Advisory Board
  - Review of student files, awardee selection
  - Center program evaluation and advice to Director

Overview

- Engineering Leadership
- Gordon Center Vision
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Leadership Qualities Addressed

Leadership Qualities Addressed

Leadership Quality	Gordon Center

Leadership Qualities Addressed

Leadership Quality	Gordon Center
Survey the market and listen to the client; Understand the issues facing society; Prepare novel product proposals; Communicate; Highest level of integrity and ethics	Undergraduate/Graduate/Professional Courses, Team-based Projects, Forums, Workshops, Summer Schools

Leadership Qualities Addressed

Leadership Quality	Gordon Center
Survey the market and listen to the client; Understand the issues facing society; Prepare novel product proposals; Communicate; Highest level of integrity and ethics	Undergraduate/Graduate/Professional Courses, Team-based Projects, Forums, Workshops, Summer Schools
Have engineering knowledge	Core engineering curricula, Summer Schools

Leadership Qualities Addressed

Leadership Quality	Gordon Center
Survey the market and listen to the client; Understand the issues facing society; Prepare novel product proposals; Communicate; Highest level of integrity and ethics	Undergraduate/Graduate/Professional Courses, Team-based Projects, Forums, Workshops, Summer Schools
Have engineering knowledge	Core engineering curricula, Summer Schools
Take risks Accept personal responsibility Recruit, motivate, educate, and engender loyalty	Challenge Projects, Case Studies

Leadership Qualities Addressed

Leadership Quality	Gordon Center
Survey the market and listen to the client; Understand the issues facing society; Prepare novel product proposals; Communicate; Highest level of integrity and ethics	Undergraduate/Graduate/Professional Courses, Team-based Projects, Forums, Workshops, Summer Schools
Have engineering knowledge	Core engineering curricula, Summer Schools
Take risks Accept personal responsibility Recruit, motivate, educate, and engender loyalty	Challenge Projects, Case Studies
Possess drive for lifelong learning	Forums, Workshops, Summer Schools, Alumni Events

Faculty Research

Joe Wang, Professor, Nanoengineering

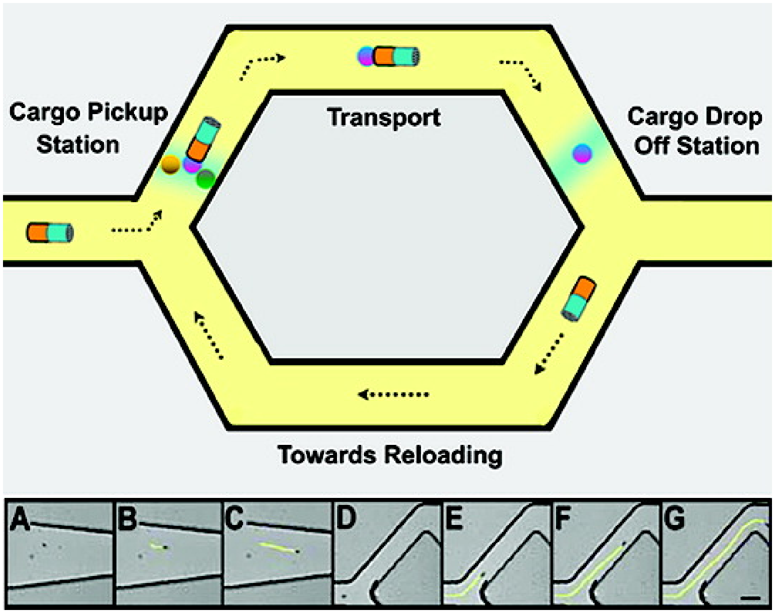
Nanomotors and Nanomachines

Review

Can Man-Made Nanomachines Compete with Nature Biomotors?

Joseph Wang

ACS Nano, **2009**, 3 (1), 4-9 • DOI: 10.1021/nn800829k • Publication Date (Web): 27 January 2009



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REVIEW

Can Man-Made Nanomachines Compete with Nature Biomotors?

Joseph Wang*

Department of Nanoengineering, University of California, San Diego, La Jolla, California 92093

ABSTRACT **Biological nanomotors have evolved over million years to perform specific tasks with high efficiency. The remarkable performance of biomotors is inspiring scientists to create synthetic nanomachines that mimic the function of these amazing natural systems. This review discusses the challenges and opportunities facing artificial nanomotors and summarizes recent progress toward the development of such man-made nanomachines. Particular attention is given to catalytic nanowire motors propelled by the electrocatalytic decomposition of a chemical fuel. While artificial nanomotors pale compared to nature biomotors, recent advances indicate their great potential to perform diverse applications and demanding tasks. Such advances include significant improvements in the velocity, motion control, cargo-towing force, and lifetime of such catalytic nanomotors. As a result, artificial nanomotors can have velocities as large as 100 body lengths per second and relatively high powers to transport a "heavy" cargo within complex microchannel networks. Despite this impressive progress, man-made nanomachines still lack the efficiency, functionality, and force of their biological counterparts and are limited to a very narrow range of environments and fuels. Improved understanding of the behavior of catalytic nanomotors will facilitate the design of highly efficient and powerful artificial nanomachines for complex operations in diverse realistic environments, leading to practical nanoscale applications in the not-so-distant future.**

KEYWORDS: nanomachines · nanomotors · nanowires · motion · biomotors · nanoscale transport · propulsion · microsystems

The use of nanomotors to power nanomachines and nanofactories is one of the most exciting challenges facing nanotechnology. Nanomotors are nanoscale devices capable of converting energy into movement and forces. Nature has created efficient biomotors through millions of years of evolution and uses them in numerous biological processes and cellular activities. Such biomolecular motors have been the subject of several excellent review articles.[1−3] Nanoscale biomotors rely on spontaneous reactions of energy-rich biomolecules, such as hydrolysis of the biological fuel adenosine triphosphate (ATP). The energy released from the ATP hydrolysis results in linear or rotational movement induced by small conformational changes. Such efficient conversion of chemical energy into mechanical work makes biological nanomachines the active workhorses in cells and enables numerous functions, ranging from intracellular transport of organelles and vesicles to large-scale muscle contractions. Due to the remarkable performance of biological motors, extensive research efforts are currently being devoted toward utilizing them in artificial microscale systems.[3] Most of the research in this area has focused on using the linear motor kinesin as a "molecular shuttle" in microfluidic devices.

Protein biomotors can be produced at extremely low cost and modified using modern biotechnological tools. A major drawback of biomolecular motors is their limited lifetime *in vitro* and the narrow range of environmental conditions that they are able to tolerate. Such limitations reflect the rapid protein degradation outside biological environments.

The remarkable performance of biomotors (along with their *in vitro* limitations) has provided an inspiration for the development of man-made nanomachines, operating on locally supplied fuels and performing various tasks.[4−8] Such artificial nanomachines are currently the subject of intense interest due to their potential applications in nanomachinery, nanomedicine, nanoscale transport and assembly, nanorobotics, fluidic systems, and chemical sensing. Some of these potential activities (*e.g.*, transport and assembly) are not very different from the cellular activities of biomotors. Transforming the concept of biological motors into engineered man-made nanomachines would require detailed understanding of the basic principles of operation of biomotors.[9−11] This is particularly challenging since biological motors are so efficient, small, and complex that they are currently beyond achievable by synthetic means.

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This review article summarizes recent progress toward the development of artificial nanomotors based on chemically powered catalytic nanowires, describes the vision of applying them for demanding activities, and discusses the challenges facing the realization of such operations. Other artificial nanotube-based rotary nanomotors[12] or mass conveyors[13] or synthetic molecular-level machines[14] or rotors,[15] performing various tasks *via* mechanical motion, fall outside the scope of this review. The goal is to encourage more researchers to tackle the challenges and share the excitement of nanomotor development and to use nature as a guide for designing future man-made nanomachines with greater sophistication.

Accordingly, in the following sections, we will address several key questions related to the development of synthetic nanomotors:

- Can we transform the basic principles of biomotors for designing powerful man-made nanomachines?
- Can artificial nanomotors compete with biological motors?
- In what environments can they function? What fuels can they use?
- Can synthetic nanomotors be powerful, versatile, and "smart" enough to perform demanding tasks and complex self-regulating operations?
- Can we integrate our nanoengines with more complex architectures, performing multiple functions?

CATALYTIC NANOWIRE MOTORS

One promising route for creating synthetic nanomachines involves fuel-driven bimetal (*e.g.*, Au/Pt) catalytic nanowire motors.[4−8,16,17] Such bi-segment nanowires are prepared by template-directed electrodeposition within the cylindrical nanopores of a porous membrane followed by the template removal. This template-assisted electrochemical synthesis allows convenient preparation of multisegment nanowires of a variety of sizes or compositions. The sequential deposition of the platinum and gold segments thus leads to asymmetric nanowires with spatially defined catalytic zones. Such asymmetry is essential for generating a directional force. The resulting nanomotors are propelled by electrocatalytic decomposition of the hydrogen peroxide fuel (on both ends of the wire), with oxidation of the peroxide fuel occurring at the platinum anode and its reduction to water on the gold cathode. This leads to a random autonomous non-Brownian movement at speeds around 10−15 μm/s toward their platinum end.[6,16,17]

Precise motion control of nanomotors is essential for performing various tasks and diverse applications. A directed motion has been accomplished by incorporating a ferromagnetic nickel segment and aligning the magnetized nanowires remotely using an external magnetic field.[17] Modulating between weak and strong magnetic fields can be used for initiating and stopping the motion, respectively, with high spatial and temporal resolution.[18] Precise steering is accomplished by controlling the orientation of the magnetic field. Catalytic nanowire motors display a chemotactic behavior in the presence of a gradient of the fuel concentration, with a directed movement and increased speed toward higher peroxide concentrations.[19] Such behavior resembles the movement of living organisms toward a chemical attractant. Controlling and modulating the local fuel level may thus be used for guiding, initiating, or slowing the motion. Recent efforts have demonstrated the use of light[20] or heat[21] to initiate and control the motion.

VOCABULARY: NANOMACHINE – A nanoscale device that performs a task • **NANOMOTOR** – A nanoscale device capable of converting energy into movement and forces • **BIOMOTOR** – A biological molecule capable of converting energy into motion and perform a funciton • **NANOWIRE** – A one-dimentsional nanostructure having a lateral size constrained to tens of nanometers (or less) and an unconstrained longitudinal size • **PROPULSION** – A force causing movement • **LAB-ON-A-CHIP** – A microchip device that integrates several laboratory functions

Various mechanisms have been proposed for the self-propulsion of bimetallic catalytic nanomotors,[5,8,22] the most accepted one being an electrokinetic self-electrophoresis.[22] This mechanism suggests that in addition to the hydrogen peroxide reduction the cathodic reaction on the gold segment involves also the four-electron reduction of oxygen to water. These cathodic reactions, along with the oxidation of the peroxide fuel at the platinum segment, result in electron flux within the wire (toward the gold cathode) and generation of an electric field (Figure 1). These lead to electromigration of protons in the electrical double layer (surrounding the nanowire) from the platinum end to the gold end and to self-electrophoresis and propulsion of the nanomotors. Such mechanism suggests good correlation between the mixed potential difference and the speed of bimetallic nanowires. This self-

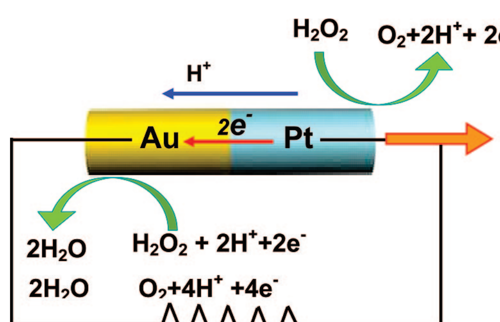

Figure 1. Self-electrophoresis (bipolar electrochemical) mechanism for the propulsion of catalytic nanowire motors in the presence of hydrogen peroxide. The mechanism involves an internal electron flow from one end to the other end of the nanowire, along with migration of protons in the double layer surrounding the wires.

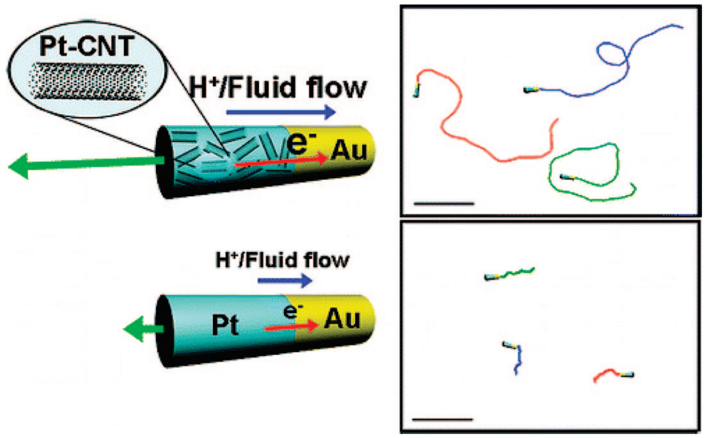

Figure 2. CNT-induced high-speed catalytic nanomotors. (Right) Tracking lines illustrating a typical motion and moving distances of Au/Pt (bottom) and Au/Pt–CNT (top) nanomotors during a period of 4 s in the presence of 15 wt % hydrogen peroxide fuel. Scale bar = 45 μm. (Left) Schematic representation of the self-electrophoresis mechanism of Au/Pt (bottom) and Au/Pt–CNT (top) bipolar nanomotors.[18]

electrophoresis mechanism has been reviewed recently.[22] A bubble-driven mechanism was considered by Ozin's group at Toronto that observed a rotary motion of Ni–Au nanowires with the gold end of the nanowire anchored to a substrate.[16] Such motion was attributed to the evolution of oxygen nanobubbles at the nickel end. The contribution of gravitational forces, associated with such bubbles' evolution, to the self-propulsion of metallic nanowires was also considered recently.[23] Other mechanisms proposed for the self-propulsion of catalytic nanomotors include an interfacial tension mechanism[6] and a Brownian ratchet mechanism in which the oxygen evolved on one segment decreases the local viscosity.[24]

TOWARD HIGHLY EFFICIENT AND POWERFUL SYNTHETIC NANOMOTORS

Efficient energy conversion is crucial for extending the scope of catalytic nanomotors to diverse operations and realistic conditions. Recent efforts have illustrated the ability to increase the velocity, force, lifetime, and versatility of synthetic nanomotors by exploring new motor and fuel compositions.[18,25]

For example, we demonstrated that the incorporation of carbon nanotubes (CNT) into the platinum segment of catalytic nanowire motors leads to a dramatically enhanced speed and power (Figure 2).[18] The resulting nanomotors are capable of moving autonomously at speeds approaching 100 body lengths per second, representing the world's fastest synthetic nanomotors.[26] Such improvement reflects the increased electrochemical reactivity of the CNT component toward the hydrogen peroxide fuel.

We also illustrated a dramatic increase of the speed of fuel-driven nanowire motors to over 100 μm/s using a cathodic Ag–Au alloy segment (instead of a pure gold one).[25] The speed of these alloy nanowire motors is strongly affected by the composition of the Ag–Au segment, with a nearly linear dependence upon changing the silver level in the growth mixture solution from 0 to 75% (v/v). Such behavior is attributed to the marked increase in the fuel decomposition rate associated with the enhanced electrochemical reactivity of Ag–Au alloys (compared to silver or gold alone).

Tailoring the fuel composition has also facilitated a dramatic speed enhancement. For example, adding a second component (hydrazine) to the peroxide fuel solution greatly increases the average speed of the Au/Pt–CNT nanowires to over 94 μm/s.[18] Other hydrazine-derived fuels indicate great promise to power nanomotors.[27]

While magnetized nanowires have been used earlier for a precise motion control,[17,18] more complex movement patterns (mimicking those of biomotors) are essential for a variety of demanding nanoscale applications. Recent studies by Mirkin[28] and Zhao[29] demonstrated the ability to control the asymmetric forces involved in fuel-driven catalytic nanomotors by exposing only one side of the catalytic metal segment or coating one face of Si nanowires with the catalytic material, respectively. Such asymmetric character of the resulting nanowires leads to rotation in the peroxide fuel bath.

TOWARD AUTONOMOUS MICROSYSTEMS: DIRECTED TRANSPORT AND CARGO MANIPULATIONS WITHIN MICROCHANNEL NETWORKS

The greatly improved velocity, motion control, cargo-towing force, and lifetime of modern catalytic nanomotors offer great promise for creating powerful on-chip microsystems powered by autonomous transport. By transporting analytes or cargo without bulk fluid flow, such nanomotors may eliminate the need for external pump or power common to pressure-driven or electrokinetic flow-based microfluidic devices and may address the challenge of fluid transport in nanofluidic systems. Biological motors, such as kinesin-powered biomolecular shuttles, have shown considerable promise for enhancing the functionality of laboratory-on-a-chip devices.[30,31] Increasing efforts are currently being devoted for designing nanoscale transport (shuttle) systems driven by motor proteins.[9,30] These biomotors exert forces in the range of 1 to 10 pN, sufficient to move large objects. Directional microchip transport of microtubules[30] or quantum dot nanocrystals[32] throughout microfabricated channels coated with kinesin has thus been demonstrated. Yet, biomotor-based microchip operations suffer from a low speed transport and a limited lifetime and require biomolecular patterning to guide the motion.

We are currently designing similar chip-based nanoscale transport and distribution systems that are driven by nonbiological nanomotors (Figure 3). Such engineered transport highways will rely on directed motion of nanowire motors and cargo manipulations (*e.g.*, precise loading and release) along predetermined traffic tracks. The improved power and speed of our catalytic nanomotors have enabled demanding microchip applications.[33] For example, in an initial proof of concept, we demonstrated the magnetically guided nanomotor motion within microchannel networks, its selective sorting in microchip intersections, and the pickup and transport and release of "heavy" cargo along predetermined paths (Figure 4, video 1). The latter relied on the incorporation of magnetic segments to enable dynamic loading and transport of magnetic-sphere cargo.

Sen's group also reported recently on the movement of sphere-loaded functionalized Pt−Au−Ni−polymer nanowires in free hydrogen peroxide solutions.[34] Coupling of the cargo spheres onto the nanomotors was accomplished through an electrostatic force between a negatively charged polypyrrole segment and a positively charged polystyrene sphere, or *via* a more selective linkage of a streptavidin-coated microsphere to nanowire functionalized with biotin-terminated disulfide (Figure 5). Other common biomolecular interactions, such as DNA hydridization, aptamer or antibody protein binding, or a nickel-histidine linking, could be employed for on-demand pickup and release of selected functional cargo. By exploiting differences in the binding strengths, such schemes should facilitate the autonomous loading/unloading of cargo without external stimuli. For example, aptamer-functionalized nanomotors could be used for selective loading of protein cargo along with the use of nucleic acid hybridization for controlled release (Figure 6). Such attachment and release mechanisms may require overcoming the high salt limitation of catalytic nanomotors. Photosensitive linkers could also be used for a light-induced cargo release. Different surface chemistries could be used for functionalizing the nanomotor and facilitating the fixation of nano/microscale cargo. The template synthesis of nanowire motors allows selective functionalization of the gold end (*e.g.*, Figure 6), as desired for carrying cargo with minimal drag force (while the nanomotor moves in the direction of the platinum end). Such functionalization could also facilitate an on-demand capture and release of a fuel-consuming enzyme (*e.g.*, peroxidase) and hence a reversible stop-and-go operation.

Microchip based on artificial nanomotors and active transport offers considerable promise for enhancing the analytical capability of laboratory-on-a-chip devices. Controlled manipulations of cargo within microchannel networks (with high temporal and spatial precision) hold considerable promise for a wide range of microchip applications, including separation and enrichment of different materials. Indeed, active transport (analogous to the one occurring in cells) represents a potentially powerful separation mechanism. Such analyte binding and manipulation capabilities should lead to enhanced microchip detection efficiency. The higher speed of our new catalytic nanowires (∼50−100 *vs* 1 μm/s of the kinesin nanomotor) indicates promise for short analysis times. Future nanomotor-based analytical microsystems could benefit also from the use of motion as a new readout (transduction) mechanism. Here, the recognition of the target analyte will trigger the release and movement of an anchored nanomotor through a displacement reaction. This should lead to remarkable sensitivity, reflecting the ability to detect single-binding events. Proper attention to the high ionic strength limitation of catalytic nanomotors is crucial for realizing such exciting bioanalytical opportunities.

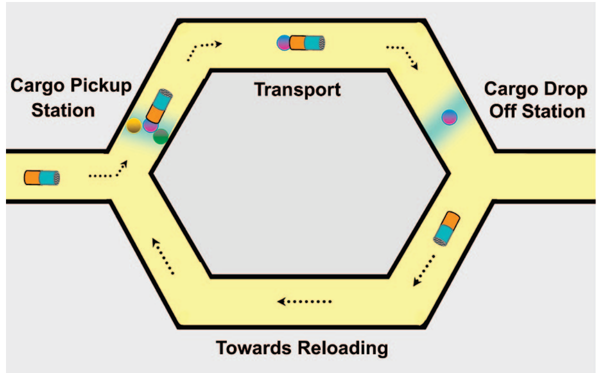

Figure 3. Nanoscale transport highway based on directed motion of artificial catalytic nanomotors and cargo manipulation (loading, transport, and delivery) along predetermined microfabricated tracks.

Synthetic nanomachines pave the way to integrated functional microdevices powered by autonomous transport and perform a series of tasks. Yet, the very few microchip demonstrations of artificial nanomotors have not been integrated into useful functional devices. Such devices would require completely autonomous and intelligent nanomotors which constantly gather information about their surroundings while navigating themselves from point A to point B within complex nanochannel ("traffic lane") networks. Current efforts in our laboratory are aimed at developing such self-

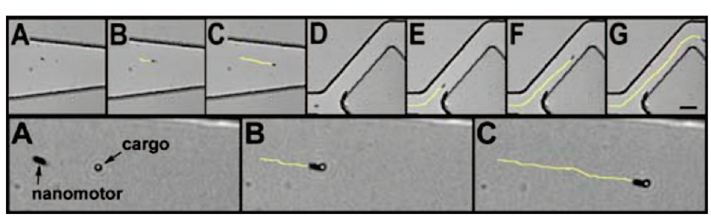

Figure 4. Optical microscopy images of the dynamic loading of a Au/Ni/Au/Pt−CNT nanomotor with a 1.3 μm diameter magnetic sphere cargo (A−C) and transport it through microfabricated (PDMS) microchannels (D−G). Scale bar in (G) = 25 μm. Bottom: magnified (×3.5) images (A−C) of the top images (A−G).[33] Video 1 is available in the html version of this paper.

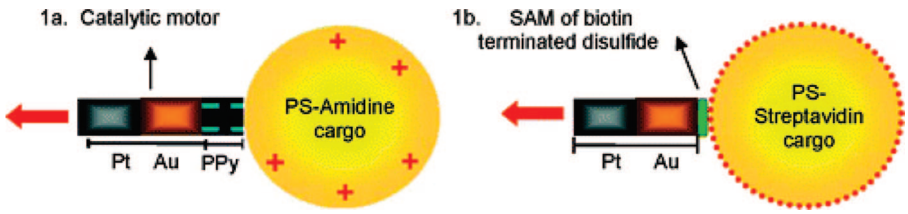

Figure 5. Cargo motor attachment by (a) electrostatic interaction between the negative polypyrrole (PPy) end of a Pt–Au–PPy motor and a positively charged polystyrene (PS) amidine microsphere; (b) biotin–streptavidin binding between the Au tips of Pt–Au rods functionalized with a biotin-terminated disulfide and streptavidin-coated cargo.[34]

controlled "smart" (environment-sensing) nanomotors based on enzyme logic-controlled motion (through control of the localized fuel concentration and movement toward high fuel levels). The decision to move through certain microchannels and the pass-code to enter into specific segments/channels will be controlled by multiple chemical signals (received from their surrounding environment), logically processed by the biocomputing system. In addition to self-adaptive navigation, the logic-controlled operation could be used for "deciding" which cargo to select, load, and deliver (*e.g.*, Figure 3).

EXTENDED SCOPE: TOWARD NEW ENVIRONMENTS AND FUELS

Chemically powered catalytic nanomotors currently operate only within a very narrow range of environments (low ionic strength aqueous solutions) and limited fuels (hydrogen peroxide, hydrazine). This limitation currently precludes many potential applications of artificial nanomotors, particularly biomedical ones. Extending the scope of synthetic nanomotors to diverse operations and wide range of environments would require the identification of new fuel sources and further improvement in the power and efficiency. The literature on fuel cells contains energy-rich reactions and redox-active fuels which can be tailored to achieve locomotion. Alternately, one may induce motion using biomolecules present in body fluids as potential fuel precursors. For example, the high (mM) concentration of glucose in body fluids can be coupled with glucose-oxidase-functionalized motors for biocatalytic generation of the peroxide fuel. Appropriate surface coatings may facilitate operation in media of higher ionic strength. The substantial improvement in power and efficiency of catalytic nanomotors should extend their scope to diverse and demanding operations and realistic conditions.

LOOKING TO THE FUTURE

The developments (described in previous sections) indicate that catalytic nanomotors offer great promise for creating self-powered practical nanomachines and provide the building blocks for realizing advanced nanoscale transport and assembly systems. Despite this impressive progress, current man-made nanomachines are still primitive compared to their biological counterparts, leaving much room for improvement. In particular, artificial nanomotors lack the sophisticated functionality of biomotors and are limited to a very narrow range of environments and fuels. Extending the scope of such motors to high ionic strength media is particularly crucial for realizing exciting biomedical opportunities. The energy-conversion efficiency of artificial nanomotors is significantly smaller (by orders of magnitude) than the energy transduction of biomotors. In addition, synthetic nanomotors require further increase in force and versatility, along with substantial size reduction. Current efforts toward achieving such improved performance involve the exploration of novel energy-rich chemical reactions, different wire compositions, geometries, and various coatings. To extend artificial nanomachines to perform more complex tasks would require an autonomous self-adaptive operation with machines cooperating and communicating with each other and making "decisions" depending on environmental conditions. The implementation of

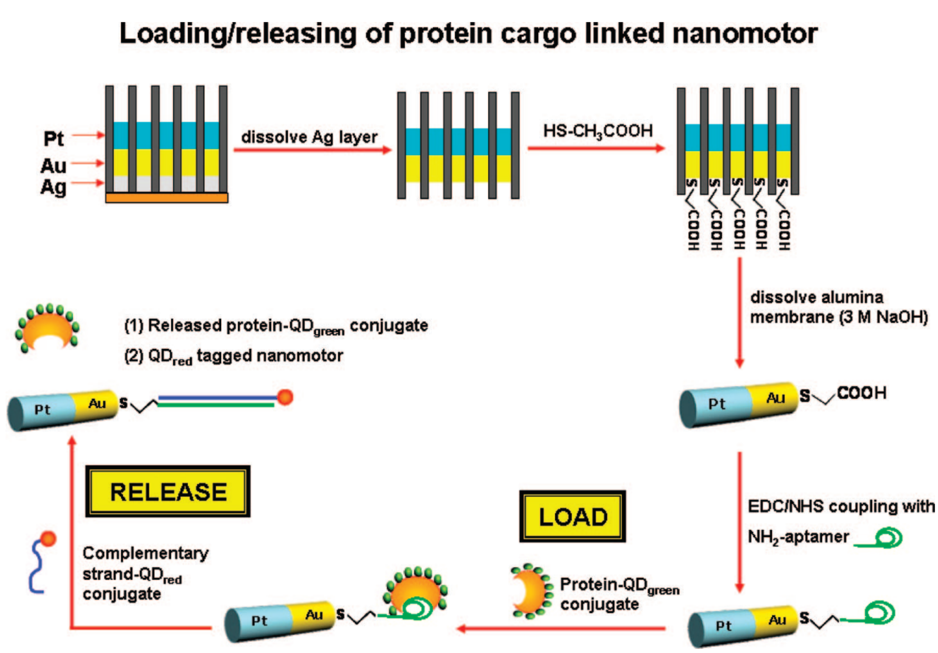

Figure 6. Use of aptamer-functionalized nanowire motors for selective binding, transport, and release of a protein cargo.

REVIEW

such autonomous self-regulated nanomotors and their integration into functional microdevices could lead to a new generation of laboratory-on-a-chip systems with unprecedented capabilities.

The improved efficiency, power, functionality, and scope of chemically powered artificial nanomotors could pave the way to exciting and important applications and to sophisticated nanoscale devices performing complex tasks. In the not-so-distant future, we expect to see self-regulated nanomachines delivering drugs or destroying toxic pollutants, motion-based ultrasensitive biosensing of disease markers or chemical agents, or nanorobots cleaning out clogged arteries. These and other exciting future applications of man-made nanomachines will be limited only by our imagination.

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REFERENCES AND NOTES

1. Schliwa, M.; Woehlke, G. Molecular Motors. *Nature* **2003**, *422*, 759–765.
2. Mavroidis, C.; Dubey, A.; Yarmush, M. L. Molecular Machines. *Ann. Rev. Biomed. Eng.* **2004**, *6*, 363–395.
3. van den Heuvel, M. G. L.; Dekker, C. Motor Proteins at Work for Nanotechnology. *Science* **2000**, *317*, 333–336.
4. Ismagilov, R. F.; Schwartz, A.; Bowden, N.; Whitesides, G. M. Autonomous Movement and Self-Assembly. *Angew. Chem., Int. Ed.* **2002**, *41*, 652–654.
5. Paxton, W. F.; Sundararajan, S.; Mallouk, T. E.; Sen, A. Chemical Locomotion. *Angew. Chem., Int. Ed.* **2006**, *45*, 5420–5429.
6. Paxton, W. F.; Kistler, K. C.; Olmeda, C. C.; Sen, A.; St Angelo, S. K.; Cao, Y. Y.; Mallouk, T. E.; Lammert, P. E.; Crespi, V. H. Catalytic Nanomotors: Autonomous Movement of Striped Nanorods. *J. Am. Chem. Soc.* **2004**, *126*, 13424–13431.
7. Ozin, G. A.; Manners, I.; Fournier-Bidoz, S.; Arsenault, A. Dream Nanomachines. *Adv. Mater.* **2005**, *17*, 3011–3018.
8. Paxton, W. F.; Sen, A.; Mallouk, T. E. Motility of Catalytic Nanoparticles Through Self-Generated Forces. *Chem.—Eur. J.* **2005**, *11*, 6462–6470.
9. Goel, A.; Vogel, V. Harnessing Biological Motors to Engineer Systems for Nanoscale Transport and Assembly. *Nat. Nanotechnol.* **2008**, *3*, 465–475.
10. Vogel, V. Reverse Engineering: Learning from Proteins how to enhance the Performance of Synthetic Nanosystems. *MRS Bull.* **2002**, *27*, 972–978.
11. Asturian, R. D. Making Molecules into Motors. *Sci. Am.* **2001**, *285*, 56–64.
12. Fennimore, A. M.; Yuzvinsky, T. D.; Han, W. Q.; Fuhrer, M. S.; Cumings, J.; Zettl, A. Rotational Actuators Based on Carbon Nanotubes. *Nature* **2003**, *424*, 408–410.
13. Regan, B. C.; Aloni, S.; Ritchie, R. O.; Dahmen, U.; Zettl, A. Carbon Nanotubes as Nanoscale Mass Conveyors. *Nature* **2004**, *428*, 924–927.
14. Kay, E. R.; Leigh, D. A.; Zerbetto, F. Synthetic Molecular Motors and Mechanical Machines. *Angew. Chem., Int. Ed.* **2006**, *44*, 72–191.
15. Kottas, G. S.; Clarke, L. I.; Horinek, D.; Michl, J. Artificial Molecular Motors. *Chem. Rev.* **2005**, *105*, 1281–1376.
16. Fournier-Bidoz, S.; Arsenault, A. C.; Manners, I.; Ozin, G. A. Synthetic Self-Propelled Nanorotors. *Chem. Commun.* **2005**, *4*, 441–443.
17. Kline, T. R.; Paxton, W. F.; Mallouk, T. E.; Sen, A. Catalytic Nanomotors: Remote-Controlled Autonomous Movement of Striped Metallic Nanorods. *Angew. Chem., Int. Ed.* **2005**, *44*, 744–746.
18. Laocharoensuk, R.; Burdick, J.; Wang, J. CNT-Induced Acceleration of Catalytic Nanomotors. *ACS Nano* **2008**, *2*, 1069–1075.
19. Hong, Y.; Blackman, N.; Kopp, N.; Sen, A.; Velegol, D. Chemotaxis of Nonbiological Colloidal Rods. *Phys. Sci. Rev.* **2007**, *99*, 178103–178107.
20. http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=112593&org=NSF.
21. Balasubramanian, S.; Kagan, D.; Manesh, K. M.; Calvo-Marzal, P.; Flechsig, G. U.; Wang, J., submitted.
22. Wang, Y.; Hernandez, R. M.; Bartlett, D. J.; Bingham, J. M.; Kline, T. R.; Sen, A.; Mallouk, T. E. Bipolar Electrochemical Mechanism for the Propulsion of Catalytic Nanomotors in Hydrogen Peroxide Solutions. *Langmuir* **2006**, *22*, 10451–10456.
23. Koutyukhova, N. I. Toward Understanding of the Propulsion Mechanism of Rod-Shaped Nanoparticles that Catalyze Gas-Generating Reactions. *J. Phys. Chem. C* **2008**, *112*, 6049–6056.
24. Dhar, P.; Fischer, Th. M.; Wang, Y.; Mallouk, T. E.; Paxton, W. F.; Sen, A. Autonomously Moving Nanorods at a Viscous Interface. *Nano Lett.* **2006**, *6*, 66–72.
25. Demirok, U.; Laocharoensuk, R.; Manesh, M.; Wang, J. Ultrafast Catalytic Alloy Nanomotors. *Angew. Chem. Int. Ed.* **2008**, *47*, 9349–9351.
26. Greenemeier, L. *Sci. Am.* May 8, 2008, On-line Edition, http://www.sciam.com/article.cfm?id=nano-hot-rods.
27. Ibele, M.; Wang, Y.; Kline, T.; Mallouk, T. E.; Sen, A. Hydrazine Fuels for Bimetallic Catalytic Microfluidic Pumping. *J. Am. Chem. Soc.* **2007**, *129*, 7762–7763.
28. Qin, L.; Banholzer, M.; Xu, X.; Huang, L.; Mirkin, C. A. Rational Design and Synthesis of Catalytically Driven Nanorotors. *J. Am. Chem. Soc.* **2007**, *129*, 14870–14871.
29. He, Y.; Wu, J.; Zhao, Y. Designing Catalytic Nanomotors by Dynamic Shadowing Growth. *Nano Lett.* **2007**, *7*, 1369–1375.
30. Clemmens, J.; Henry Hess, H.; Doot, R.; Matzke, C.; Bachand, G.; Vogel, V. Motor-Protein "Roundabouts": Microtubules Moving on Kinesin-Coated Tracks Through Engineered Networks. *Lab Chip* **2004**, *4*, 83–90.
31. Doot, R. K.; Hess, H.; Vogel, V. Engineered Networks of Oriented Microtubule Filaments for Directed Cargo Transport. *Soft Matter* **2007**, *3*, 349–356.
32. Bachand, G. D.; Rivera, S. B.; Boal, A. K.; Gaudioso, J.; Liu, J.; Bunker, B. C. Assembly and Transport of Nanocrystal CdSe Quantum Dot Nanocomposites using Microtubules and Kinesin Motor Proteins. *Nano Lett.* **2004**, *4*, 817–821.
33. Burdick, J; Laocharoensuk, R; Wheat, P. M.; Posner, J.; Wang, J. Synthetic Nanomotors in Microchannel Networks: Directional Microchip Motion and Controlled Manipulation of Cargo. *J. Am. Chem. Soc.* **2008**, *130*, 8164–8165.
34. Sundararajan, S.; Lammert, P. E.; Zudans, A. W.; Crespi, V. H.; Sen, A. Catalytic Motors for Transport of Colloidal Cargo. *Nano Lett.* **2008**, *8*, 1271–1276.

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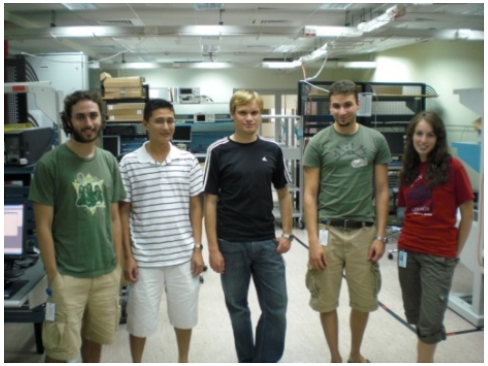

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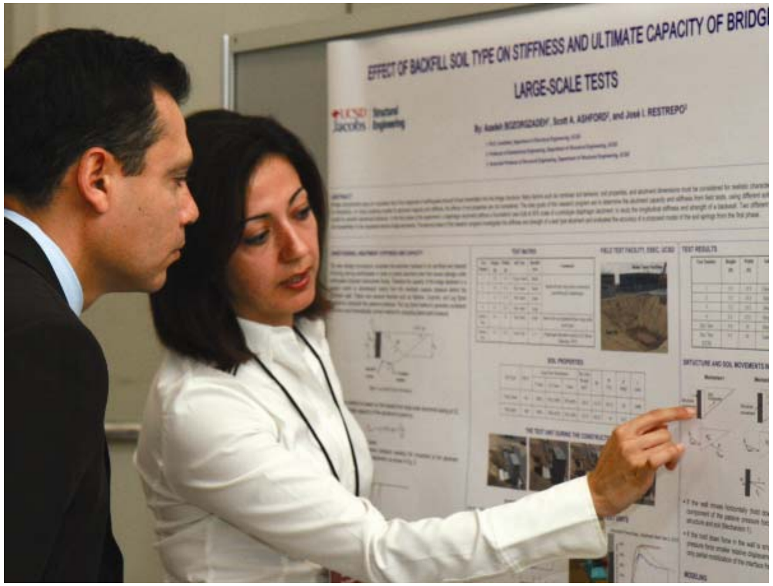

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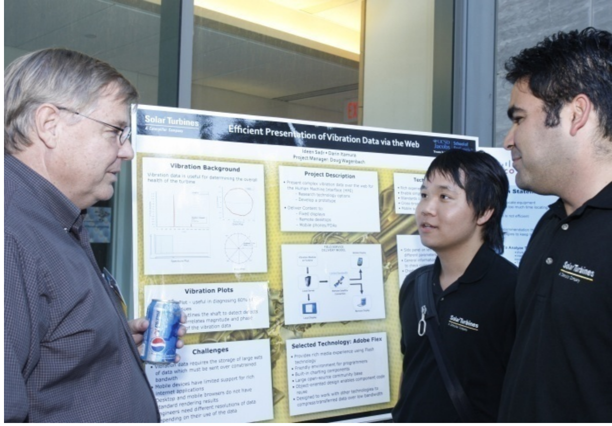

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