The Adolph C. and Mary Sprague

Miller Institute

for Basic Research in Science

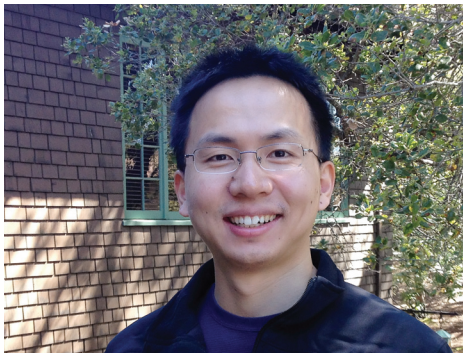
Newsletter
Spring 2014

Creating Terradynamics of Locomotion in Real-World Terrains

Miller Fellow Focus: Chen Li

Locomotion is one of the defining behaviors of animals. To survive, almost all animals move in their environment to find food, mate, habitat, and escape predators. The terrain in which animals move is often spatially complex and temporally dynamic. Many surfaces (e.g., soil, sand, mud, snow, rubble) are multi-phased mixtures of discrete solid particles and fluids, and can yield and flow under during locomotion. Other surfaces (e.g., grass, bushes, leaf litter) are highly cluttered with multiple three-dimensional components, and present challenging obstacles for locomotion. While we have gained significant understanding of terrestrial locomotion on simple flat, solid ground like treadmills and running tracks, we know surprisingly little about how animals move through their complex, dynamic terrain, largely due to lack of understanding of the physics of interaction with these complex, dynamic terrain. Therefore, better understanding of this physics can advance the biology of terrestrial animals in their natural environments.

Better understanding of this physics can also help us create better bio-inspired mobile robotic devices for real world applications. Similar to the



information age brought about by personal computers and the Internet over the last 40 years, today mobile robots are on the verge of becoming a major part of society. Recent advancements in technology is promising a new generation of mobile robots for applications as diverse as manufacturing, logistics, agriculture, environmental surveillance, healthcare, public safety, military, search and rescue, planetary exploration, research and education, and consumer products. However, while existing mobile robots (which dominantly use wheels) can operate effectively on controlled, idealized surfaces (e.g., hard floor, paved road), their locomotor performance is still generally poor in highly complex, cluttered, and dynamic terrain, either natural (e.g., desert, forest), artificial (e.g., stairs, disaster sites), or even extraterrestrial (e.g., Martian soil). By contrast, terrestrial animals (which

CONTINUED ON PAGE 2 >

Inside this edition:

Call for Nominations

Miller Research Fellowship Nominations
Deadline: Wednesday, September 10, 2014

Miller Research Professorship Applications
Deadline: Thursday, September 18, 2014

Visiting Miller Professorship Departmental Nominations
Deadline: Friday, September 19, 2014

For more information on all our programs:
MillerInstitute.berkeley.edu

"The Miller Institute is unique in its impact on science, advancing the frontiers of knowledge... effective in its cross-disciplinary impact by standing on the capabilities of some of the best scientists in the world, from junior researchers to seasoned professionals."

- Raymond Jeanloz

Geophysicist, Miller Professor Fall 1992, Miller Institute Executive Director 1998-03, MacArthur Prize, National Academy of Sciences, Miller Senior Fellow 2011-2016

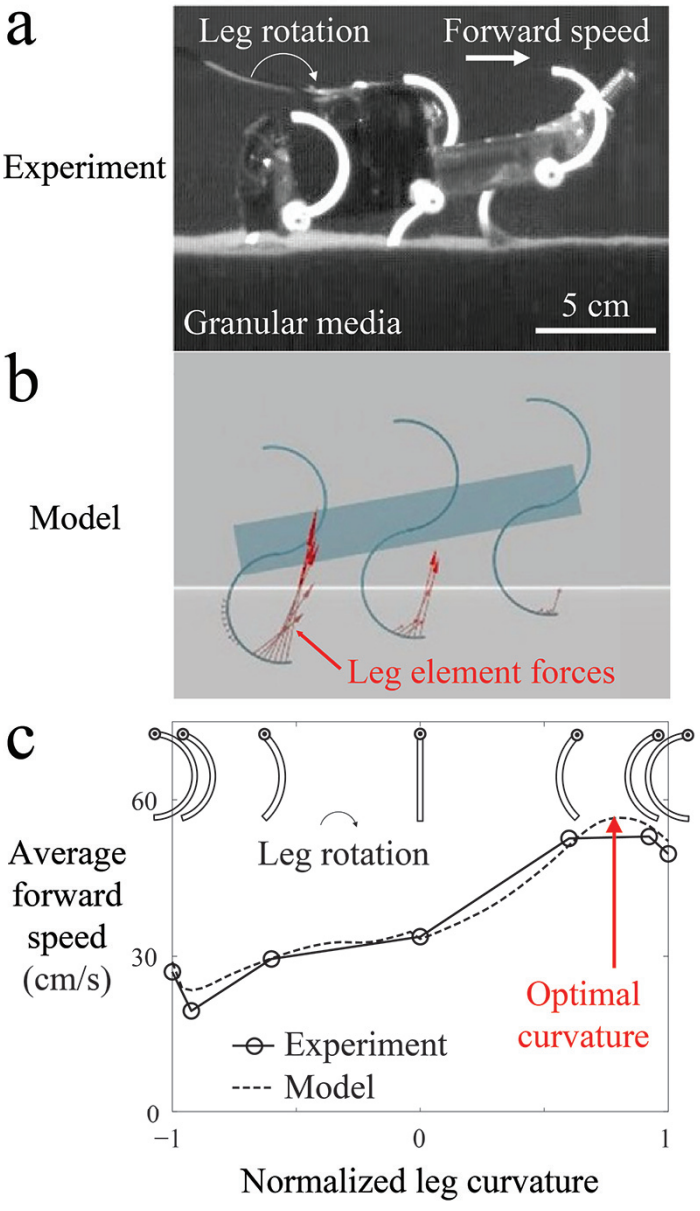
> CONTINUED FROM PAGE 1 [Miller Fellow Focus]

dominantly have legs) nimbly move about in almost all kinds of terrain, and therefore provide excellent inspirations for making better mobile robots.

Miller Fellow Chen Li's research aims to discover the physics principles of how animals move in their complex, dynamic terrain, and apply these principles to create bio-inspired robots with locomotor capabilities approaching those of animals in the real world. As a physicist, Chen takes a principled approach by precise and repeatable control of both the terrain and the locomotor to better measure and model locomotor-terrain interaction. His PhD research at Georgia Tech centered on understanding legged locomotion on granular media such as sand and gravel, a typical type of challenging terrain that can flow during locomotion. Chen developed a novel apparatus to control and vary the compaction of granular media to mimic the full range of loose to compact sand occurring in deserts and beaches, much like the well-established wind tunnel and flow tanks for studying flight and swimming. He also used bio-inspired legged robots as physical models of animals to control and vary locomotor kinematics and morphology. Through a series of experiments, Chen discovered how legged locomotor performance sensitively depended on both locomotor parameters (e.g., leg kinematics and morphology) and ground properties (e.g., compaction), much like the case of swimming and flight in fluids.

Chen then focused on creating the first terradynamics, a general physics model analogous to aero- and hydrodynamics for fluids, to allow quantitative prediction of forces and movement during locomotion on granular media. To do this, Chen and his colleagues took inspiration from an old fluid mechanics theory called the resistive force theory, initially developed for modeling nematodes and sperms swimming in water by undulating their bodies. For these low Reynolds number swimmers, fluid inertia is negligible, and the fluid forces acting on them are dominated by fluid viscosity. Thus the fluid forces are local, i.e. the fluid force acting on one element of the animal is independent of those acting on other elements. Therefore, one can simply superpose all element forces to obtain the net force on the entire organism, and determine its swimming speed by balancing thrust with drag. For granular media, at typical speeds of small animals and robots, grain inertial is also negligible, and forces are dominated by friction. So it is plausible that the same superposition principle may be applied to locomotion on or within granular media.

Figure 1. Terradynamics predicts forces and movement during legged locomotion on granular media like sand. (a) A bio-inspired hexapedal robot running on granular media. (b) The robot's ground reaction force is calculated by superposition of element forces over the body and legs using the resistive force model. (c) Model predicts the speed of the robot over a broad range of leg curvatures, and predicts the optimal leg curvature.



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The Adolph C. and Mary Sprague
Miller Institute for Basic Research in Science
University of California, Berkeley

Call for Nominations: Miller Research Fellowship

2015-2018 Term

Nomination Deadline: September 10, 2014

The Miller Institute for Basic Research in Science invites department chairs, faculty advisors, professors and research scientists at institutions around the world to submit nominations for Miller Research Fellowships in the basic sciences. The Miller Institute seeks to discover and encourage individuals of outstanding talent, and to provide them with the opportunity to pursue their research on the Berkeley campus. Fellows are selected on the basis of their academic achievement and the promise of their scientific research. Miller Fellows also have a keen curiosity about all science and share an appreciation for an interdisciplinary experience. The Miller Institute is the administrative home department for each Miller Fellow who is hosted by an academic department on the Berkeley campus. All research is performed in the facilities provided by the UC Berkeley academic department. A list of current and former Miller Research Fellows can be found at: http://MillerInstitute.berkeley.edu/all.php?nav=46

Miller Research Fellowships are intended for exceptional young scientists of great promise who have recently been awarded, or who are about to be awarded, the doctoral degree. Normally, Miller Fellows are expected to begin their Fellowship shortly after being awarded their Ph.D. A short period as a post-doctoral fellow elsewhere does not exclude eligibility. However, applicants who have already completed substantial postdoctoral training are unlikely to be successful except in unusual circumstances. **A nominee cannot hold a paid or unpaid position on the Berkeley campus at the time of nomination or throughout the competition and award cycle**. Nominees who are non-US citizens must show eligibility for obtaining J-1 Scholar visa status for the duration of the Miller Fellowship. The Miller Institute does not support H1B visa status. The Fellowship term must commence between July 1 and October 1, 2015. Eligible nominees will be invited by the Institute to apply for the Fellowship. Direct applications and self-nominations are not accepted.

*All nominations must be submitted using the Online Nomination System at: http://**MillerInstitute.berkeley.edu**

Nominators will need the following required information to complete the online nomination process:

- Nominee's complete full and legal name
- Nominee's current institution
- Nominee's complete and current active E-mail address, current mailing address and telephone number
- Nominee's Ph.D. Institution and (expected) Date of Ph.D. (month & year required)
- Letter of recommendation and judgment of nominee's promise by the nominator (saved in pdf format). The Executive Committee finds it helpful in the recommendation letter to have the candidate compared with others at a similar stage in their development.
- Nominator's current active E-mail address, title, and professional mailing address (include zip code/campus mail code)

The Institute provides a stipend of $63,000 with annual 2% increases and a research fund of $10,000, for total compensation of $73,000 annually. There is provision for travel to Berkeley for Miller Fellows and their immediate families and a maximum allowance of $3,000 for moving personal belongings. Benefits, including medical, dental, vision and life insurance are provided with a modest contribution from the Miller Fellow. All University of California postdocs are represented by the UAW. Fellowships are awarded for three years, generally beginning August 1, 2015 and ending July 31, 2018. Approximately eight to ten Fellowships are awarded each year. Candidates will be notified of the results of the competition starting in mid-December, and a general announcement of the awards will be made in the spring.

We are grateful for your thoughtful participation in this process and hope that you regard the time you may devote to this effort justified by the contribution you will be making to the careers of distinguished young scientists.

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Miller Research Fellowship Awardees 2014-2017

The Miller Institute is pleased to introduce the 2014-2017 Miller Research Fellows. Each year, the Miller Institute seeks to discover individuals of outstanding talent and to bring to Berkeley young scholars of great promise. Candidates are nominated for these awards and are selected on the basis of their academic achievement and the potential of their scientific research. The Fellows will be working with Berkeley faculty hosts for a three-year term beginning in the 2014 academic year. A full list of all past and present Miller Fellows is available on our website.

Elaine Angelino
Ph.D. - Harvard University
Berkeley Dept.: EECS
Faculty Host: Michael Jordan

A central tool for scientific data analysis is inference, the process of uncovering structure in data. However, traditional inference procedures have not scaled to handle massive datasets or complex mathematical representations of structure. My research lies at interface of computer science and statistics, and is focused on developing new algorithms and theory to make large-scale inference feasible.

Michelle Antoine
Ph.D. - Albert Einstein College of Medicine
Berkeley Dept.: MCB/HWNI
Faculty Host: Hillel Adesnik

I will be investigating how disturbances in the balance between excitatory and inhibitory synaptic transmission within cortical circuits influence sensory perception and computation.

Inbal Ben-Ami Bartal
Ph.D. - University of Chicago
Berkeley Dept.: Psychology
Faculty Host: Dacher Keltner

Empathy, the ability to recognize and share the emotional state of another, is the foundation of life in social groups. Empathy leads to helping behavior, cooperation, and social learning, and strengthens the group as a whole. The empathic response is rooted in evolutionarily ancient processes, and shared across diverse mammalian species. Dr. Ben-Ami Bartal researches the neurophysiological mechanisms underlying the empathic response. Using an integrative approach that includes data from humans and rodents, she seeks to explain the means by which observing another in distress activates a stress response in the observer, and engages pro-social motivation.

Carson Bruns
Ph.D. - Northwestern University
Berkeley Dept.: Chemistry
Faculty Host: Matthew Francis

Nature has optimized the efficiency of photosynthesis by evolving an exquisite hierarchical protein network that arranges hundreds of pigments in circular arrays, which absorb sunlight and efficiently transfer the energy to neighboring arrays and reaction centers. My research involves the modification of virus capsid proteins with synthetic molecules and pigments to create light-harvesting arrays inspired by Nature's example. These synthetic modifiers are rationally designed with self-assembling and photophysical properties that impart the corresponding virus-based light-harvesting arrays with the ability to (i) self-assemble into predetermined nanostructures, and (ii) efficiently harvest and transfer solar energy. This strategy for constructing protein-based biomimetic materials is relevant to emerging applications ranging from nanofabrication to artificial photosynthesis.

Kestutis Cesnavicius
Ph.D. - M.I.T.
Berkeley Dept.: Mathematics
Faculty Host: Kenneth Ribet

I am interested in arithmetic geometry, which is an area of mathematics that lies at the interface of number theory and algebraic geometry. Specifically, I employ techniques from algebraic geometry and representation theory to study the arithmetic of abelian varieties together with various related questions.

Tijmen de Haan
Ph.D. - McGill University
Berkeley Dept.: Physics
Faculty Host: William Holzapfel

Galaxy clusters are the largest gravitationally collapsed structures in the universe. Their abundance is a powerful tracer of the underlying properties of the universe. Using the 10-m South Pole Telescope, Tijmen de Haan studies the subtle distortions in the cosmic microwave background to discover hundreds of new galaxy clusters and their impact on our knowledge of the expansion history and energy content of the universe.

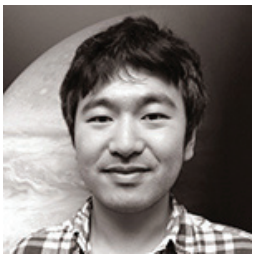
Sebastian Höhna
Ph.D. - Stockholm University
Berkeley Dept.: Statistics
Faculty Host: Rasmus Nielsen

Natural selection indirectly acts on the genome by favoring individuals with advantageous features, so called traits, and penalizing individuals with disadvantageous features. These traits rise and fall in frequency in populations and with them their linked gene(s). The traces of past selective events can still be observed in genomes of present day species. My research focuses on the development of statistical and computational methods to infer which parts of the genome have been under deviating strength of selective pressures and the correlation between these genome segments and observed traits by especially focusing on the joint inference of homologous (shared by ancestry) molecular characters, evolutionary histories, rates of selection and trait evolution.

Ryan Trainor
Ph.D. - California Institute of Technology
Berkeley Dept.: Astronomy
Faculty Host: Mariska Kriek

The evolution of galaxies to the present day was driven by complex interactions of dark matter, stars, gas, and black holes. Ryan uses optical and infrared telescopes to quantify the results of these interactions, including the production of elements synthesized through star formation. In particular, his research focuses on galaxy formation in the neighborhoods of extremely active supermassive black holes, or quasars, where the energy released from accreting matter can both violently terminate star formation and illuminate protogalactic gas clouds that would otherwise be undetectable with current instruments.

Da Yang
Ph.D. - California Institute of Technology
Berkeley Dept.: EPS
Faculty Host: David Romps



Moist convection - in essence, thunderstorms - is a fundamental process on Earth, yet it is one of the most difficult processes to model and one of the least well understood. Da is interested in developing quantitative theories of moist convection by building idealized mathematical models of moist convection and simulating its interaction with large-scale atmospheric flows. These studies will help to improve the representation of moist convection in climate models and renew our confidence in climate forecasting.

Norman Yao
Ph.D. - Harvard University
Berkeley Dept.: Physics
Faculty Host: Dung-Hai Lee

Statistical mechanics is the formalism that connects thermodynamics to the microscopic world. It governs familiar every day processes ranging from heat transport and electrical conductivity to the diffusion of gases. In isolated quantum systems, the breakdown of statistical mechanics is known as many-body localization. Dr. Yao is interested in the understanding the associated phase transition and in proposing both systems and observables with which to probe this phenomenon. The realization of such a phase of matter may enable the protection of exotic topological orders and holds potential as a strongly-interacting, disordered, many-body quantum computer.

Call for Nominations:

Miller Research Fellowship 2015-2018

Online Nomination Deadline: Wednesday, Sept. 10, 2014

http://MillerInstitute.berkeley.edu

(More information online & on PAGE 3)

In the News

Edward Frenkel (Miller Professor Spring 2013)
was interviewed by Stephen Colbert on April 7. The show was broadcast on Comedy Central and is posted online.

Adam Summers (Miller Fellow 1999-2001)
was highlighted on Science Friday, 4/3/2014, for his research in clearing and staining fish.

Eugene Chiang (Miller Professor Fall 2013)
has received the **2014 Distinguished Teaching Award** at UC Berkeley.

Alex Filippenko (Miller Fellow 1984-1986, Miller Professor Spring 1996, 2005)
was featured in the UC Berkeley News Center for his work on a newly discovered bright supernova in a nearby galaxy.

Lawrence Hall (Miller Fellow 1981-1983, Miller Professor Fall 1995),
Jesse Thaler (Miller Fellow 2006-2009),
Lisa Randall (Visiting Miller Professor 2011-2012),
Riccardo Barbieri (Visiting Miller Professor Fall 1994) &
Yasunori Nomura (Miller Fellow 2000-2002),
among others, participated in the powerful and highly praised documentary, "Particle Fever".

Dmitry Budker (Miller Professor 2002-2003, Fall 2012) &
Ron Folman (Visiting Miller Professor Fall 2013)
were featured on the UC Berkeley News Center for showing that diamond sensors can measure the tiny magnetic fields in high-temperature superconductors, providing a new tool to probe these much ballyhooed but poorly understood materials.

Feng Wang (Miller Fellow 2005-2008)
was featured on the UC Berkeley Research site for his work using carbon to control light. Feng Wang has been developing optoelectronics for faster computing.

Heino Falcke (Visiting Miller Professor Fall 2006)
was awarded an **ERC Synergy Grant**. The European Research Council (ERC) has awarded 14 Million Euros to a team of European astrophysicists to construct the first accurate image of a black hole. The team will test the predictions of current theories of gravity, including Einstein's theory of General Relativity.

Daniela Kaufer (Miller Professor Fall 2012)
was featured on the UC Berkeley News Center for her work: "Seizing Control of Brain Seizures". She was also featured for her work which provides evidence that chronic stress predisposes brain to mental illness.

Eske Willerslev (Visiting Miller Professor Spring 2015)
was featured on NPR discussing the topic: Ancient DNA Ties Native Americans From Two Continents To Clovis.

Theodor Agapie (Miller Fellow 2007-2009)
was named a recipient of the **Presidential Early Career Awards** for Scientists and Engineers, the highest honor bestowed by the United States Government on science and engineering professionals in the early stages of their independent research careers.

Alex Zettl (Miller Professor 1995 & 2007)
was the winner of the 2013 **Feynman Prize**. The award recognizes his exceptional work in the fabrication of nanoscale electromechanical systems (NEMS), spanning multiple decades and including carbon nanotube-based bearings, actuators, and sensors brought to fruition with cutting-edge nanoscale engineering.

George Leitmann (Miller Professor 1966-1967)
was awarded the **Austrian Cross of Honor for Science and Art, First Class** & the **Chevalier de la Legion d'Honneur**, France.

Lynn Ingram (Miller Professor 2003-2004)
was featured on the UC Berkeley News Center for her work on the state's water woes.

Linyou Cao (Miller Fellow 2010-2013)
was awarded the **NSF Career** award. The NSF will provide funds to Cao's research project, "Van der Waals Epitaxial Heterostructures: Beyond 2D Materials".

Peter Molnar (Visiting Miller Professor Fall 2005)
was awarded the **2014 Crafoord Prize** in Geophysics.

Ray Jayawardhana (Miller Fellow 2000-2002)
was appointed Dean for the Faculty of Science at York University in Toronto, Canada.

Melissa Wilson Sayres (Miller Fellow 2011-2014) &
Kirk Lohmueller (Miller Fellow 2010-2013)
were featured on the UC Berkeley News Center for their study that dispels theories of the Y chromosome's demise.

Miller Senior Fellows Panel

The Miller Senior Fellowship program was created to recognize outstanding Berkeley faculty and to enjoy their interactions at Miller Institute events. A secondary goal was to have the MSF impart their wisdom and share their experience with the Miller Research Fellows. In March, Senior Fellows Barbara Meyer, Raymond Jeanloz, Saul Perlmutter and Gabor Somorjai shared their personal experiences on a variety of topics including their biggest scientific blunders, staying motivated, managing personal relationships within collaborations, and overseeing graduate students and postdocs during a panel discussion and dinner with the Miller Fellows.

Call for Applications & Nominations

Miller Research Professorship 2015-2016

Online Application Deadline: Thursday, Sept. 18, 2014

Applications from UC Berkeley faculty for Miller Research Professorship terms in the 2015-16 academic year will be accepted online beginning in June 2014. The purpose of the Professorship is to release members of the faculty from teaching and administrative duties and allow them to pursue research on the Berkeley campus. Appointees are encouraged to follow promising leads that may develop in the course of their research.

Applications are judged competitively and are due by Thursday, September 18, 2014. It is anticipated that between five to eight awards will be made.

Visiting Miller Research Professorship AY15-16

Online Nomination Deadline: Friday, Sept. 19, 2014

The Advisory Board of the Miller Institute for Basic Research in Science invites Berkeley faculty to submit online departmental nominations for Visiting Miller Research Professorship terms in Fall 2015 or Spring 2016. The purpose of the Visiting Miller Professorship is to bring promising or eminent scientists from any place in the world to the Berkeley campus on a short-term basis for collaborative research interactions.

Online nominations will be accepted beginning in June 2014 and are due by Friday, September 19, 2014.

:: **Nomination & Application details**: MillerInstitute.berkeley.edu

:: **Questions?** Kathryn Day: 510-642-4088 | millerinstitute@berkeley.edu

Miller Fellow Focus

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However, unlike for fluids where the fluid forces can be derived from fluid dynamics, no such general force models had existed for granular media. To solve this problem, Chen measured the resistive forces acting on an element intruder as it moves through granular media, and determined how forces depend on intruder parameters including depth, orientation, speed, and movement direction. By integrating element forces over the body and appendages of animals and robots (Fig. 1b), Chen and his colleagues discovered that the resistive force model can accurately predict net forces on the locomotor and thus predict movement on granular media (Fig. 1a). They also demonstrated that the model is useful in device design by predicting the optimal leg shape of the robot for running fastest on granular media (Fig. 1c).

The resistive force model that Chen and his colleagues established is the first general physics model to predict forces and movement during locomotion on granular media, and marked the creation of terradynamics, a new research area analogous to the well-established aero- and hydrodynamics for predicting forces and movement in fluids. This terradynamics is broadly applicable to diverse animals and robots of arbitrary morphology and kinematics, because it is based on superposition of element forces. This terradynamics is also broadly applicable to a diversity of granular media, as demonstrated by Chen's force measurements in various granular materials of different particle size, shape, density, friction, compaction, and polydispersity. Therefore, this terradynamics provides an ideal tool for biologists to understand animal locomotion and for engineers and roboticists to design and test the devices.

Currently at Berkeley, Chen (Miller Fellow 2012-2015) is taking the next step to create a broader terradynamics for terrain with three-dimensional, multi-component obstacles, by developing physics models to describe the energy landscape of locomotor interaction with these terrains. Working with host Robert Full in Integrative Biology, Chen created a new apparatus to parameterize and control compliant beams, the first to mimic complex, dynamic natural obstacles such as grass and bushes. Through his experiments and physics models, he discovered that insects like cockroaches have body shapes that help them avoid energy barriers and access energy valleys to quickly traverse dense "forests" of beams. Chen is also working with co-host Ronald Fearing in EECS to apply this principle to create insect-inspired robots with exoskeleton that allow them to traverse similar obstacles without sensory feedback.

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Spring Dinner

At the Institute's Spring Dinner, Professor Robert Full presented a talk entitled, "BioMotion: Bipedal Bugs, Gripping Geckos and Leaping Lizards Inspire Robots". He demonstrated his robots for Miller Fellows Brooke Gardner, Amy Shyer & Ashivni Shekhawat.

Obituaries

Sydney Kustu (Miller Professor 2005-2006) passed away on March 18, 2014.

Gareth Thomas (Miller Professor 1964-1965) passed away on Feb. 7, 2014.

Roderic Park (Miller Professor 1969-1970) passed away on Sept. 9, 2013.

Make a Gift

Private donations are becoming an increasingly significant resource for the Miller Institute. Your personal investment in support of the future of the Miller Institute will be greatly appreciated. Visit our: **"Make a Gift"** page at: ***MillerInstitute***.*berkeley.edu*/**gift**

The Miller Institute is "dedicated to the encouragement of creative thought and the conduct of research and investigation in the field of pure science and investigation in the field of applied science in so far as such research and investigation are deemed by the Advisory Board to offer a promising approach to fundamental problems."

For More Information:
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