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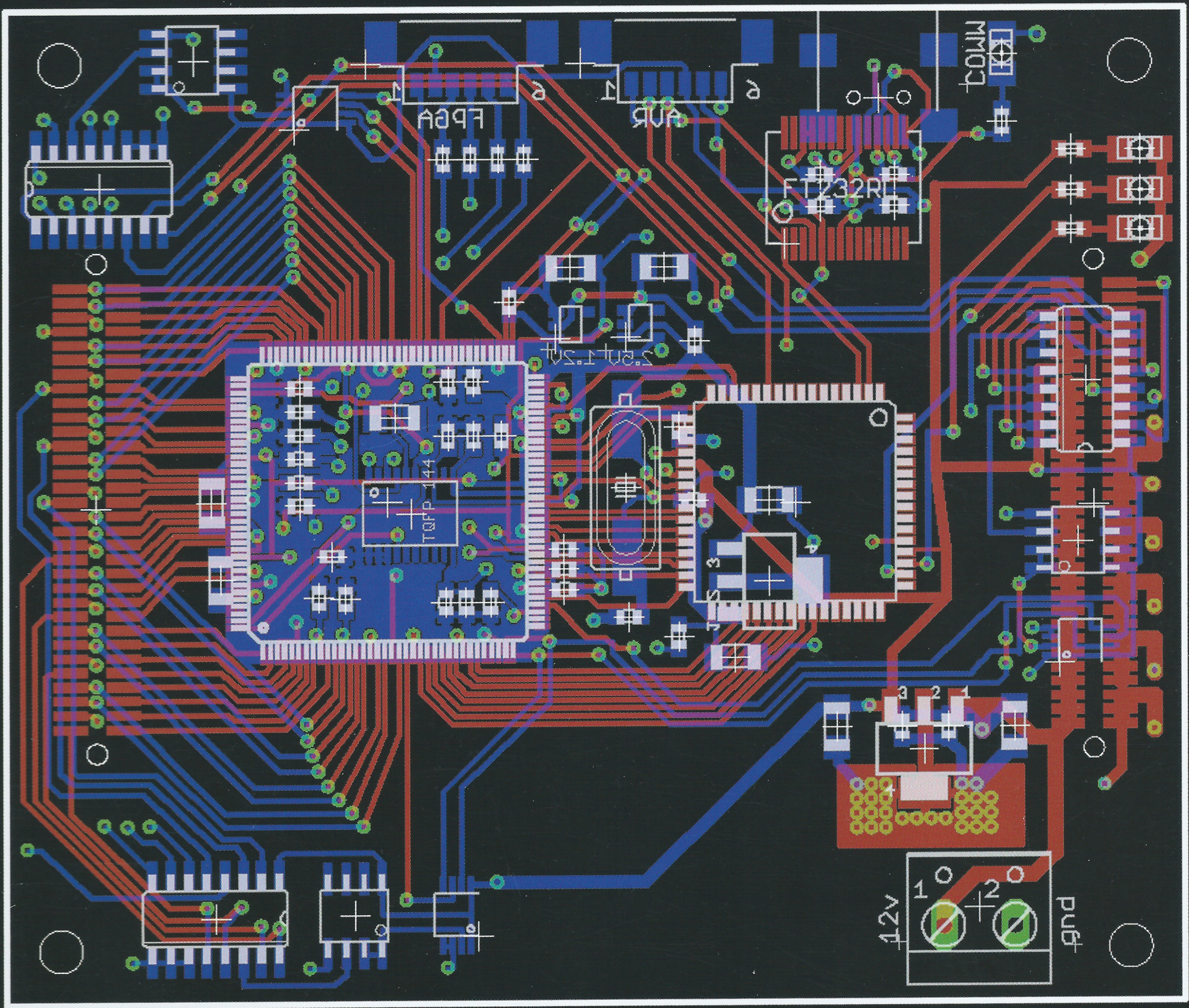
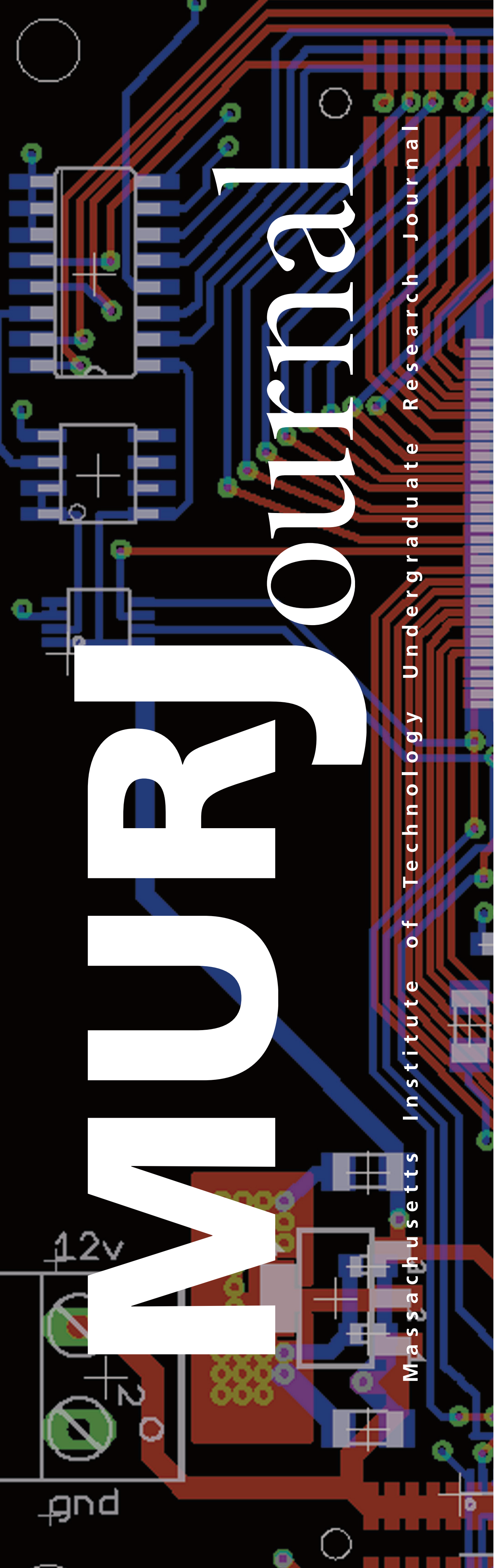
MURJ Journal

Massachusetts Institute of Technology Undergraduate Research Journal



Chips, Scooters, and Asteroids

Massachusetts
Institute of
Technology



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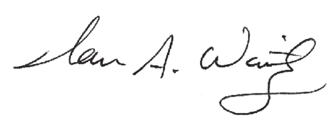
Cover: A computer motherboard.
Photo taken by Jeff Lieberman.

At MIT, we really are rocket scientists. I mean this both figuratively and literally: people at MIT do things no one else can; and some of us build rockets and design systems to put humans 50 million miles from home in an atmosphere devoid of oxygen, where a communication with Mom and Dad will take 30 minutes round trip. ("Hello? I didn't hear what you just said, the coverage must be bad here.") But even as we continue to explore the universe, all around MIT there is a growing movement to solve the great social and environmental challenges here on Earth. As evidence, I have to look no farther than my own department (Aero-Astro), where the largest funded research area is now energy and the environment.

This great span of challenges, from those here on Earth to those at the far reaches of the universe, is reflected in the research described in this 17th issue of the MIT Undergraduate Research Journal (MURJ). The issue includes wonderful contributions from Courses 2, 6, 8, 12, 16, and 22: a self-balancing scooter developed by undergrads working with high school students; a low-cost, portable, human-powered vacuum device that enabled the Jaipur Foot Organization to implement a rapid prosthetic fitting technique in rural areas of Indochina; structurally-flexible organic field-effect transistors; an exploration of the likelihood that an observer could evolve in universes that differ from ours only in the values of the light quark masses; research on wireless energy transfer between satellites for constellations of many small satellites that work collaboratively; development of a fluid flow simulation based on statistical representations of the relationships among molecules; and a feedback control system to better isolate the Laser-Interferometer Gravitational-Wave Observatory from seismic disturbances. Indeed, rocket science.

It is the energy and excellence of our students that make MIT the bright center of an increasingly technology-enabled universe. World-class research plus undergrads: MIT has no peer in this regard. It is an honor to introduce this 17th issue of MURJ.



Institute Professor Ian Waitz

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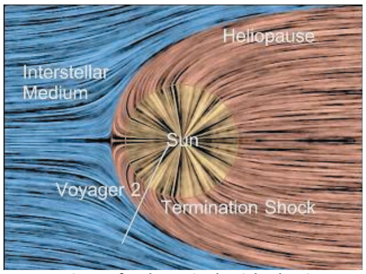
PSB 08-03-0169

MIT Science News In Review

[Physical Sciences]

Voyager 2 Reveals Surprises

Developed at MIT in the 1970s, the Plasma Science instrument on the *Voyager 2* spacecraft has given way to revelations about the boundary zone marking the end of the sun's influence in space. The spacecraft had passed the termination shockwave formed by the collision of solar wind and interstellar gas. The first of these discoveries is the unexpectedly strong magnetic field in the interstellar region that is generated by the thin gas. This field distorts the expected uniform spherical shape formed by the outflowing gas from the sun.



Interaction of solar wind with the interstellar medium (ISM).

Credit: John Belcher and Mark Bessette, MIT, via MIT Tech TV.

The second revelation was the discovery of a significantly cooler temperature than expected just outside the boundary. Scientists hypothesized that this anomaly may be caused by energy becoming particles that are hotter than what can be measured by the Plasma Science instrument. Built for only five-year missions, *Voyager 2* has lasted thirty years and is expected to function properly until 2020. It is now passing through a region called the heliosheath, which is a region where the solar winds are interacting with the interstellar medium. In the next decade or so, it is estimated to cross into the heliopause, where the solar outflow ends. When it reaches that point, the spacecraft will be able to measure, for the first time, data from the interstellar medium, which is unaffected by the sun's magnetism and wind, for the first time. *Voyager 2* has also been able to make detailed measurements of the solar wind's temperature, density, and speed through repeated encounters with the shockwave.

Voyager 2 is now 7.9 billion miles from Earth traveling at 35,000 miles per hour.

—M. Yen

Source: "MIT instrument finds surprises at solar system's edge"
http://web.mit.edu/newsoffice/2007/voyager-1210.html

Eco and Urban Friendly Scooter

An efficient, compact, simple, and portable scooter has been developed by the members of MIT's Smart Cities group in collaboration with ITRI, Taiwan's Industrial Technology Research Institute, and SYM, a Taiwan based scooter manufacturer. The goal, as head designer William J. Mitchell, the Alexander W. Dreyfoos Professor of Architecture and Media Arts and Sciences stated, "was all about providing a clean, green, and silent electric scooter that would provide, even better, the same kind of urban mobility."

Low cost, foldable scooters shown here in Milan.

Credit: Michael Chia-Liang Lin, Smart Cities, MIT Media Lab

Design factors, such as placing the motors inside the wheels, have made it possible for the scooter to store, fold, and roll like a trolley suitcase, a bonus for crowded urban and city life. Furthermore, the number of spare parts for the scooter has been reduced from around the normal 1000 to only 150, which would bring down production costs as well. Two different models are being produced for the future, one a refinement of the current folding scooter introduced in Milan, and another lower cost version, without folding capability, for developing countries. The whole design project was completed in eight months under a cross-disciplinary team.

MIT's electric scooter. The left view displays the folded up scooter.

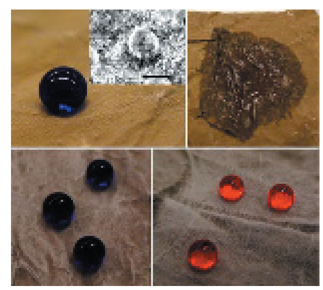
Credit: MIT Smart Cities Group

—P. Ramaswamy

Source: "Cuter scooter defined by electricity, portability"
http://web.mit.edu/newsoffice/2007/scooter-1127.html

Oil-Repelling Material

Researchers at MIT have developed a material that can repel oil, with significant applications for aviation, hazardous waste cleanup, and space travel. Because no natural sources of oil-repelling materials exist, it was especially challenging to create an oleophobic surface. The major problem developers overcame with creating the material was the low surface tension of hydrocarbons, which causes oil to spread out over surfaces. They designed materials with microfiber molecules called fluoroPOSS that cushion liquid droplets; when a drop of oil falls on the surface, the fibers prevent it from touching the opposite side and wetting it.



Top left: drop of water forms a bead on a lotus leaf. Top right: drop of hexadecane soaks lotus leaf. After the leaf is coated with MIT's oil repelling material, both the water and hexadecane form beads on the lotus leaf (see bottom photos).

Credit: Anish Tuteja and Wonjae Choi, MIT

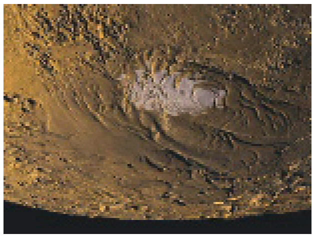
With the inclusion of other design parameters, the researchers will be able to create optimized surfaces that will repel different types of hydrocarbons. The Air Force, which funded the research and developed fluorPOSS, is interested in using this technology to protect machine components from jetfuel. Lead developers were Anish Tuteja, Wonjae Choi, Minglin Ma, Professor Gregory Rutledge, and Joseph Mabry and Sarah Mazzella from the Air Force Research Laboratory at the Edwards Air Force Base.

—P. Ramaswamy

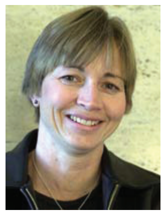
Source: "MIT creates oil-repelling materials"
http://web.mit.edu/newsoffice/2007/surfaces-1206.html

Mars Polar Caps Contain Water

New findings have confirmed that Mars, second only to Earth, contains the largest deposits of frozen water in the inner solar system. Because carbon dioxide makes up a vast majority of the atmosphere with trace amounts of water, researchers previously believed that frozen carbon dioxide was the predominant solid under a layer of dust at the polar caps. A team led by Maria Zuber, an MIT professor of geophysics, calculated the density of the southern polar caps and the surrounding smooth layer deposit regions using topographical and gravitational data from the three Mars orbiters. They estimated the density to be 1220 kilograms per cubic meter, data consistent with a mixture of water with approximately 15% silicate dust. A similar study will be conducted on the northern ice caps. The puzzle of the polar caps may be soon solved by these further studies. This research was funded by the NASA Mars Program.



Mars polar ice cap.
Credit: NASA/MOLA Science Team



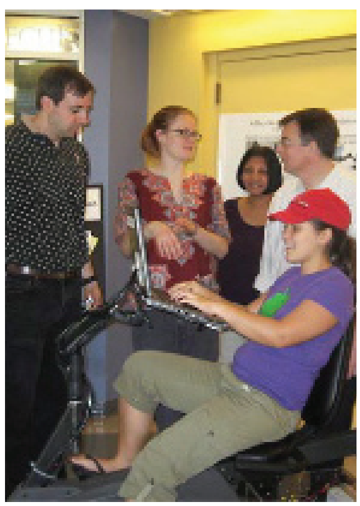
Maria Zuber.
Credit: Donna Coveney

—P. Ramaswamy

Source: "MIT observations give precise estimate of Mars surface ice"
http://web.mit.edu/newsoffice/2007/mars-0921.html

Pedal Powered Laptops

MIT students have made multitasking a breeze by creating a fitness laptop where the user can burn calories while recharging the laptop using pedaling power. The project began as a class assignment in the Spring 2007 class Introduction to Civil and Environmental Engineering Design (1.102). Team members Piotr Fidkowski, Sebastian Figari, Sarah John, Kendra Johnson, Julia Kiberd, Tina Lai, and Devn McCorkle wanted to connect a standard exercise bike to a dorm Athena computer (computer for student use). Using a laptop donated by Dell, the team altered the exercise bike to allow the wheels to generate power and charge a conventional 12-volt battery, with mechanisms for electricity regulation to prevent overcharging. Replacing the usual handlebars, the laptop rests atop a tray. With continuous pedaling, the bike generates sufficiently more than the 30 watts of power required to run a laptop. The students hope to place their invention at the fitness center in the MIT's Stata Center. This project was part of the IT Energy@MIT Initiative, which began in March 2007.



MIT student Julia Kiberd '08 checks her email while creating power for her computer by pedaling a bicycle.
Credit: Laxmi Rao

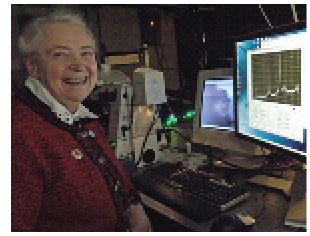
—P. Ramaswamy

Source: "Students get charge out of pedal power"
http://web.mit.edu/newsoffice/2007/energy-laptop-1108.html

Thermoelectric Cooling

Using the properties of thermoelectric cooling, MIT Institute Professor Mildred S. Dresselhaus and colleagues have created a material that can control temperatures locally, leading to energy savings. When a voltage is applied to these devices, they become hot on one side and cold on the other instead of the temperature equalizing quickly. In addition, they can generate a voltage when heated. These thermal and electrical properties need to be separated in order to improve the efficiency of this process.

The major challenge in creating efficient cooling materials is that they need to be good electrical conductors without generating much heat. In this manner, the research team embedded tiny, nano-sized particles in a matrix of a different, altered semiconductor material. While electricity can flow freely, the patterns of particles do not allow heat to flow properly, therefore controlling the distinct properties. These thermoelectric materials have numerous applications, from more efficient car engines to electronic products. They can also be used to decrease the noise of appliances such as air conditioning.



Professor Mildred Dresselhaus, in the spectroscopy lab at MIT.
Credit: Donna Coveney

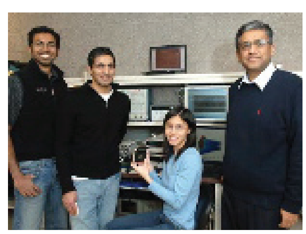
—W. Morejon

Source: "Thermoelectric materials are one key to energy savings"
http://web.mit.edu/newsoffice/2007/nanoenergy-1120.html

Almost No Energy Required

Through collaboration with Texas Instruments, an MIT research team has developed a proof-of-concept chip design that is up to ten times more energy-efficient than present portable electronics technology. Circuits on these microchips have to be able to function properly at a much lower voltage level than usual; the standard chip operates at around 1 V while the new design can operate at voltages as low as 0.3 V. Even though this is a major breakthrough, it also presents the problem of building a high-efficiency DC-DC converter into the chip so that the voltage can be reduced to a lower level without a requiring greater number of separable components. In addition, imperfections and variability in the manufacture of the chip have a greater effect on its performance at lower voltage levels.

The applications of this technology range from implantable medical devices to tiny military sensor networks that can be dispersed in a battlefield. The goal is to have the power requirements such that ambient energy, such as body heat, would be enough to power the chip. On February 5, the chip design was presented at the International Solid-State Circuits Conference in San Francisco by Joyce Kwong, an Electrical Engineering and Computer Science graduate student at MIT. Other team members included MIT colleagues Professor Anantha Chandrakasan, Yogesh Ramadass and Naveen Verma.



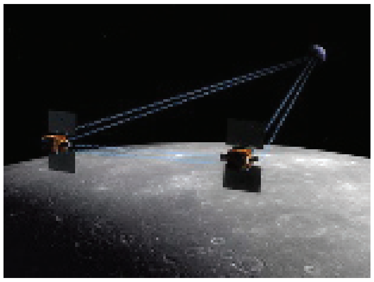
The team that developed the microchip. From left, electrical engineering graduate students Yogesh Ramadass, Naveen Verma and Joyce Kwong, along with Professor Anantha Chandrakasan.
Credit: Donna Coveney

—M. Yen

Source: "Team develops energy-efficient microchip"
http://web.mit.edu/newsoffice/2008/energy-chip-0205.html

The Holy Grail of the Solar System

The Gravity Recovery and Interior Laboratory (GRAIL) mission, led by MIT professor Maria Zuber, is set to launch in 2011. This $375 million project aims to map the interior of the moon and record its thermal history by placing two satellites into orbit around the moon. The satellites will map variations in the moon's gravitational pull, which will reveal varying densities in the crust and mantle. The mission will also measure the relative timing of and the effects of the impacts that created craters, allowing scientists to further understand the formation of the inner planets due to the uneroded surface of the moon.



The twin GRAIL satellites.

Credit: JPL - NASA.

To measure gravitational field changes, the GRAIL mission will monitor the changes in distance between the two satellites. These measurements will be almost a thousand times more precise than those made by previous technologies. The team has developed new technologies ensuring the precise monitoring of radio signals to calibrate the timing of the satellites accurately. Such technology can be applied to future planetary mapping missions to Mars, which would reveal the movement of water below the planet's surface. Information about lunar gravity can also be used to facilitate future missions to the moon, find better landing sites, and program safer descents.

This mission also has an educational outreach component, headed by Sally Ride, the first American female astronaut. Five live MoonKam cameras have been installed on each satellite, allowing middle school classrooms access to close-up photographs and videos of the moon's surface.

Impressed by GRAIL's revolutionary technology, NASA selected this MIT-led team from two dozen proposals. Lockheed Martin Space Systems of Denver, Colorado will build and operate this satellite system.

—M. Yen

Source: "MIT to lead ambitious lunar mission"

http://web.mit.edu/newsoffice/2007/moon-1214.html

Exoskeleton Lightens Burdens

Researchers in the MIT Media Lab's Biomechatronics Group, led by associate professor Hugh Herr, recently created a device to alleviate the physical stress of backpacks and other heavy loads. The team's "exoskeleton" attaches to its wearer at the ankle, knee, and hip and has been shown to assume 80% of an 80-pound load. While other research teams have developed similar models, most require a large power source (approximately 3,000 watts). In contrast, the MIT team's device requires only one watt of energy. The researchers hope that their device will reduce the risk of injury to soldiers and others who frequently carry heavy equipment.

While the exoskeleton reduces the effective weight of the wearer's load, it also impedes the walker's natural gait and subsequently causes a 10% increase in oxygen consumption. The researchers hope to alter their design to allow the walker to retain his natural gait.

—G. Denman

Source: "21st-century pack mule: MIT's 'exoskeleton' lightens the load"

http://web.mit.edu/newsoffice/2007/exoskeleton-0919.html

Energy-Efficient Gas Sensor

MIT professor and Microsystems Technology member Akintunde Ibitayo Akinwande is leading a group of MIT engineers as well as a team of international scientists to enhance the efficiency of a sensor able to detect traces of harmful gases in the environment. The sensor functions by splitting gas molecules into ions by either adding or removing electrons and passing them through an electric field, where the sensor is able to detect the produced voltage. Current designs take roughly fifteen minutes to report results; Akinwande's team hopes to reduce this time to about four seconds.

Graduate student Conor Walsh demonstrates a prototype of the 'exoskeleton' he and other MIT researchers have devised.

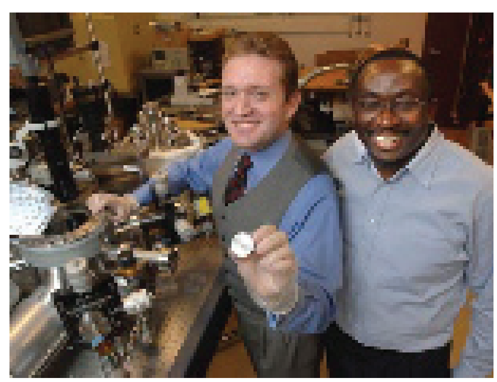
Credit: Samuel Au

One major challenge is reducing the energy needed to create a vacuum through which these molecules can be passed. Current models use up to 10,000 joules of energy and are the size of a paper grocery bag. Akinwande is hoping to shrink their sensor down from the size of a computer mouse to that of a matchbox, which would cut the energy needed to run it to four joules. Energy conservation is not the only benefit, however; smaller gas detectors are easier to use and more likely to pick up trace amounts of gases in the air than large detectors. The applications of this revised model range from the detection of harmful substances in the air to the protection of materials maintained under seas. Akinwande and his team plan to complete the final product within two years.

—W. Morejon

Source: "MIT gas sensor is tiny, quick"

http://web.mit.edu/newsoffice/2008/micro-analyzer-0110.html



MIT research scientist Luis Velasquez-Garcia, left, and Akintunde Ibitayo Akinwande, professor of electrical engineering and computer science, developers of the sensor.

Credit: Donna Coveney

World Science News In Review

[Physical Sciences]

Worldwide effort to develop robotic rats for rescue missions

Recently, nine groups of robotics and brain researchers from throughout Europe, Israel, and the U.S. have joined together in a quest to better understand animal sensory. Researchers hope that a deep understanding of the neurological pathways that create senses in animals will lead to the development of robotic animals that can aid in rescue missions. Nocturnal animals have been the main focus due to the fact that such animals must rely on an excellent sense of touch when vision is not available. Rats have become a special interest to researchers due to the acute sense of touch that their whiskers provide as well as their small size, which would make them useful for reaching places that humans cannot in various rescue missions. The problem that the researchers have encountered is that the neurological make-up of rat's whiskers consists of a triple layered and parallel feedback system with the rats receiving each signal in a combination of horizontal, vertical, and radial interpretations. Researchers have found it particularly difficult to reproduce the neurological complexity of rat whiskers because they do not yet fully understand the multiple feedback systems involved. Research teams are currently continuing experimentations and are drawing on theoretical mathematics and physics to help solve their problem.

—I. Lucero

Source: "Scientists from Europe, Israel and the US develop robotic rats to aid in rescue missions"
http://www.eurekalert.org/pub_releases/2008-02/wios-sfe021008.php

Battery life: 10-fold increase

The ubiquitous lithium-ion battery has been reinvented with a staggering ten-fold increase in the amount of electricity it can produce. Researchers from Stanford University, in a paper published in the December 16 issue of Nature Nanotechnology, reported achieving this feat by incorporating silicon nano-wires instead of carbon at the anode of a Li-ion cell.

The amount of lithium that can be stored at the anode (typically made of carbon) of a Li-ion battery is the primary factor affecting storage capacity. Silicon has a greater storage capacity, but undergoes swelling and shrinking cycles during charging and use respectively, causing the Si-films to pulverize and degrade battery performance. Nanotechnology helped counter this seemingly unresolvable problem, with silicon nano-wires. Though they do expand four times on soaking lithium, they do not fracture.

Apart from turbo-charging laptops, this new avatar of lithium ion batteries may find applications in electric cars and energy storage generated by rooftop solar panels. Yi Cui, the lead researcher, is optimistic that the technology can be implemented on commercial scale quickly owing to "the mature infrastructure behind silicon" and is working towards that end.

—B. Sagar

Source: "Stanford's nanowire battery holds 10 times the charge of existing ones"

http://www.eurekalert.org/pub_releases/2007-12/su-snb121807.php

Splitting Water

Researchers at Penn State University have designed a proof-of-concept device that will obtain hydrogen directly from water using solar cells. In a presentation at the American Association of the Advancement of Science (AAAS) meeting in Boston on February 17, the team reported developing a catalyst-dye complex that mimics the electron transfer and water oxidation processes in photosynthesis. The complex contains a center catalyst of iridium oxide molecules surrounded by orange-red dye molecules in a two-nanometer diameter cluster.

Electrons in the dye are excited by incident light and then split water molecules with the help of the catalyst. Each surface iridium atom cycles through the process 50 times a second, a thousand times faster than any other catalyst, at a frequency comparable to the turnover of Photosystem II in photosynthesis. In the hydrogen cell, the catalyst saturated on titanium oxide was used as the anode and platinum as the cathode.

The water splitting requires 1.23 volts, but in the present configuration, 0.3 volts need to be supplied from outer sources. The efficiency of the system is 0.3%, although researchers expect to achieve 10-15% solar-conversion efficiency with catalytic systems.

—B. Sagar

Source: "Solar cell directly splits water for hydrogen"
http://www.eurekalert.org/pub_releases/2008-02/ps-scd021108.php

Movement-Powered Electronics

Futuristic garments, woven out of nanotech-based fabrics that harvest energy from body movements and even a light breeze, will soon obviate the need for recharging batteries in devices such as mp3 players. In a paper published in the February 14 issue of Nature, a team of scientists from the Georgia Institute of Technology has reported the ability to generate electric current by flexing pairs of fibers coated with ZnO.

The fiber-based nanogenerator utilizes the semi-conductive properties of ZnO nano-wires and the piezoelectric effect. The nanogenerators are made of Kevlar fibers on which ZnO nano-wires have been grown radially outwards. One of the fibers in each pair is also coated with gold, which serves as an electrode. The fibers produce current when the ZnO nano-structures and gold bristle together. According to Zhong Lin Wang, the lead researcher of the study, the power output can be as much as 80 milliwatts per square meter of fabric, enough to power a small iPod or charge cell phones.

However, washing clothes would be tricky, as ZnO degrades when wet. Researchers are working on combining multiple fibers to increase voltage and current levels and increasing the conductance of fibers. This research builds on the nano-wire nanogenerator developed by the team last April and was funded by the National Science Foundation and the Department of Energy.

—B. Sagar

Source: http://www.nytimes.com/reuters/technology/tech-nanoshirt.html?_r=1&em&ex=1203138&oref=slogin

Strontium Atomic Clock Breaks Record for Accuracy

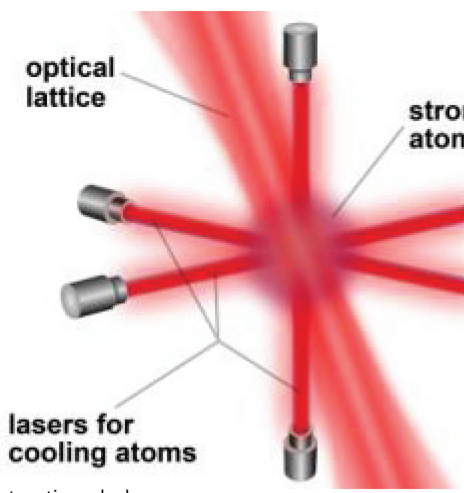
JILA, a joint institute of NIST and the University of Colorado at Boulder has developed an experimental strontium based atomic clock that has surpassed the accuracy of NIST F-1 standard cesium clock. The JILA strontium clock will not be ahead or behindS by a second in 200 million years, compared to the figure of 80 million for NIST F-1. The development was facilitated by the presence of a critical mass of time-keeping expertise and equipment in the Boulder – comparison with nearby atomic clocks helped the research.

The clock consists of a few thousand strontium atoms held in a column of about 100 pancake shaped traps called "optical lattice". The "lattice" forms sort of an artificial crystal of light to constraint atom motions and systematic errors. It is formed by standing waves of intense near-infrared laser light. On tick (and that is 430 trillion times a second) consists of bathing the atoms in very stable red laser light at the exact frequency that prompts jumps between two electronic energy levels. The use of higher-frequency optical light compared to microwaves in NIST F-1 provides better precision.

Atomic clocks are critical for synchronizing telecom networks, deep space communication and designing new gravity sensors to test the fundamental laws of the universe. The study was published in the February 14 issue of Science Express.

—B. Sagar

Source: "Collaboration helps make JILA strontium atomic clock 'best in class'"
http://www.physorg.com/news122220149.html



JILA's strontium clock.
Credit: Greg Kuebler/JILA

Searching for Earth-like Planets

Recent findings suggesting that rocky planets may be far more common than previously thought were presented at the American Association for the Advancement of Science (AAAS) in Boston this past February. According to Michael Meyer from the University of Arizona, "between 20-60% of Sun-like stars have evidence for the formation of rocky planets not unlike the processes we think led to planet Earth". His team used the US space agency's Spitzer space telescope to examine groups of stars with masses similar to the Sun's and detected discs of cosmic dust around stars in some of the youngest groups they surveyed, which they believe to be a by-product of rocky debris colliding and merging to form planets.

According to Alan Stern of NASA, "Our old view that the Solar System had nine planets will be supplanted by a view that there are hundreds if not thousands of planets in our Solar System." Thousands of objects have already been discovered in the Kuiper belt alone, many of which rival the planet Pluto in size, and it is even possible that other Earth-like planets might allow human colonies to be established on them--or even contain life themselves.

The search for earth-like planets.
Credit: BBC News

The key to finding these planets, according to Debra Fischer of San Francisco State University, California, is the "Goldilocks zone", a region of space in which the planet is just the right distance from its parent star that its surface is neither too-hot or too-cold to support liquid water.

—A. Chuong

Source: "Planet-hunters set for big bounty"
http://news.bbc.co.uk/2/hi/science/nature/7249884.stm

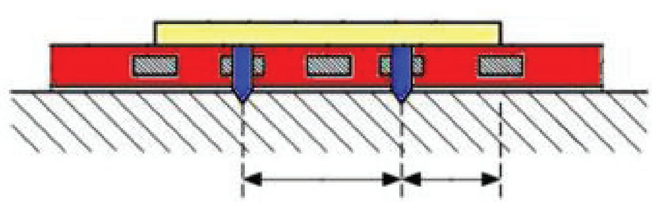
Wallpaper Outlets

Philips researchers have recently designed a conducting wallpaper which will allow electrical devices to be plugged in almost anywhere on a wall. While other researchers have designed similar materials, Philips' wallpaper is unique in that it provides a range of device voltages, which can be accessed at different positions on the wall. The wallpaper has metallic conducting stripes running through the material and draws power from an external electrical supply. Electrical devices are then connected through the use of contact pins, allowing voltage levels to be modulated.

In addition, the wallpaper is not only limited only to walls. According to the company's patent application, it could also be attached to ceilings and floors as well. Ultimately, the applications this wallpaper has for interior design are dramatic and wide-ranging. It not only allows homeowners the aesthetic advantages of regular wallpaper, but also gives consumers the option of moving furniture and electronic appliances without the confining limits of wall outlets and behind-the-wall wiring.

—A. Chuong

Source: "Wired Wallpaper Offers Alternative to Outlets"
http://www.physorg.com/news122029910.html



Conducting wallpaper.
Credit: physorg.com

New Advances in Superconductivity

An international team composed of researchers from the Université de Montréal, ETH Zurich, University of Notre Dame, University of Birmingham, U. K., Los Alamos National Laboratory and Brookhaven National Laboratory has discovered that magnetic fields can interact with electrons in superconductors in new ways. By using the Swiss Spallation Neutron Source (SINQ), the team was able to cool a single crystal sample of CeCoIn5 to temperatures just 50 mK above absolute zero. They then applied a magnetic field high enough to almost completely suppress superconductivity and found that the core of the vortices features electronic spins partly aligned with the magnetic field.

According to Professor Andrea D. Bianchi of the Université de Montréal, "these materials produce a completely new type of magnetic tornado that grows stronger with increasing fields rather than weaken" and it is the first experimental evidence supporting a theory describing the properties of superconducting vortices – a theory for which Abrikosov and Ginzberg received the Nobel Prize in 2003. While most superconductors are able to operate without resistance due to the interaction of electrons with crystal, it is generally believed that superconductivity in this new cobalt and indium substance is a result of magnetic interactions between electrons. The applications of this discovery for modern technology are dramatic and wide ranging. As Professor Bianchi noted, "This discovery sharpens our understanding of what, literally, holds the world together."

—A. Chuong

Source: "New understanding for superconductivity at high temperatures"
http://www.eurekalert.org/pub_releases/2008-01/uom-nuf011008.php

The 12,000-Lens Camera

Led by Abbas El Gamal, Professor in the Department of Electrical Engineering, researchers at Stanford University have developed a camera that vastly improves on the standard two-dimensional images that current models produce. In fact, not only will the camera produce three-dimensional images, it is also able to give the exact distances between it and any object in the photograph.

Gumal and his team have enabled the creation of this "depth-map" by substantially reducing the size of standard pixels to 0.7 micrometers, allowing for more lenses to fit in the same area as that allotted for today's cameras. In fact, the Stanford creation has a total of 12,616 micro-lenses, each able to be considered as its own "camera". The device is nearly equivalent in size to current digital cameras and uses no lasers.

Researchers are already looking into the applications of the multi-lens apparatus. The precise measurement of distances between the camera and photographed objects seems to be the most intriguing feature of the design, specifically fields such as facial recognition for security and artificial intelligence. With the ability to pinpoint exact distances of surrounding objects, robots could eventually have better vision than humans.

—W. Morejon

Source: "Stanford researchers developing 3-D camera with 12,616 lenses"
http://www.eurekalert.org/pub_releases/2008-03/su-srd031908.php

An "EPIC" Solution to Piracy

Researchers at the University of Michigan and Rice University recently devised a new method of protecting top-of-the-line microchips from black-market hardware piracy. This method—dubbed "EPIC" (Ending Piracy of Integrated Circuits) by its creators—aims to increase chips' security without affecting their performance or power consumption. An EPIC-capable chip would simply have a few extra switches that act as a sort of combination lock on the chip. Chips would not work properly until activated with the proper passkey, which would be uniquely generated by the chip itself.

The goal of EPIC, according to its creators, is not to create a completely "uncrackable" security system for microchips. Rather, EPIC seeks to achieve the more practical goal of ensuring that it costs much more to reverse engineer the security mechanism than it does to simply license and produce the chip legally.

—P. Baranay

Source: "Unique Locks On Microchips Could Reduce Hardware Piracy"
http://www.sciencedaily.com/releases/2008/03/080305173345.htm

Recent Discoveries in Nanomaterials

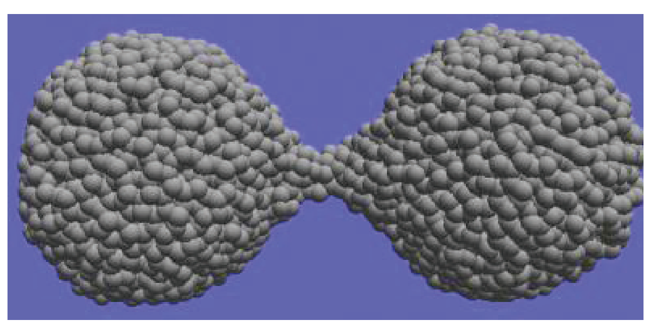
Nanoscientists at the National Institute of Standards and Measures have uncovered even more shocking differences between how materials act at the nanoscale compared to the macroscale. Traditionally, materials are classified as either brittle or ductile depending on their ability to maintain their shape and structural integrity when stressed. Brittle materials tend to fail earlier than ductile materials due to miniscule flaws in their structure.

Researchers, however, have discovered that these miniscule flaws barely, if at all, exist at the nanoscale. Moreover, nanomaterials consist almost completely of surface atoms, which are more mobile than non-surface atoms because they are not completely bounded by other atoms. Together, these two factors lend surprising ductility to materials that are generally brittle at the macroscale (such as silica).

These results were tested by two different groups of researchers. The first group used an atomic force microscope to investigate the interfacial structure of silica., concluding that silica's macroscopic properties do not accurately predict its highly ductile strength on the nanoscale. The second group of researchers, on the other hand, employed computer simulations that confirmed the first group's results and suggested that the mobility of surface atoms is indeed at least partially responsible for the remarkable properties of nanomaterials. Though the researchers claim their work is very basic, they hope their results will eventually help to enhance the design of microelectronic mechanical devices.

—P. Baranay

Source: "Nanomaterials Show Unexpected Strength Under Stress"
http://www.sciencedaily.com/releases/2008/03/080312141241.htm

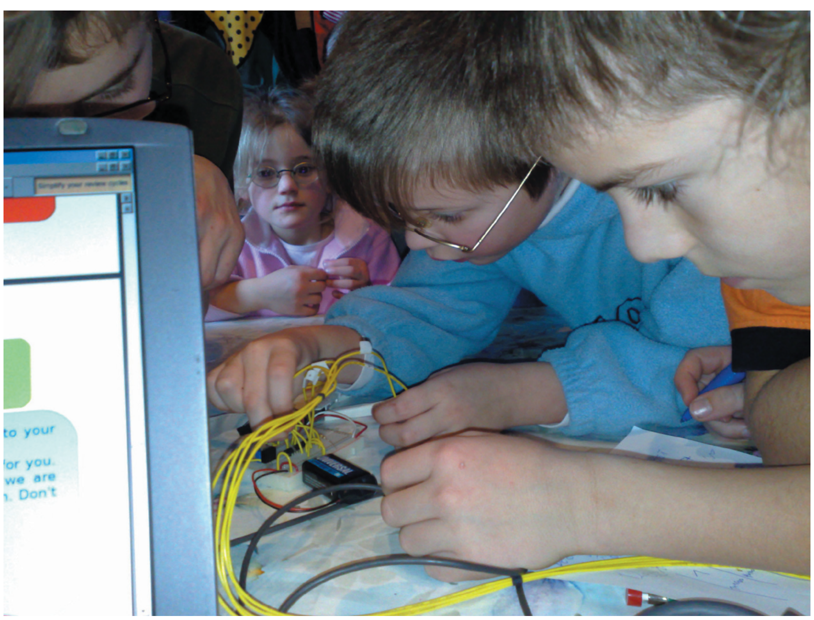


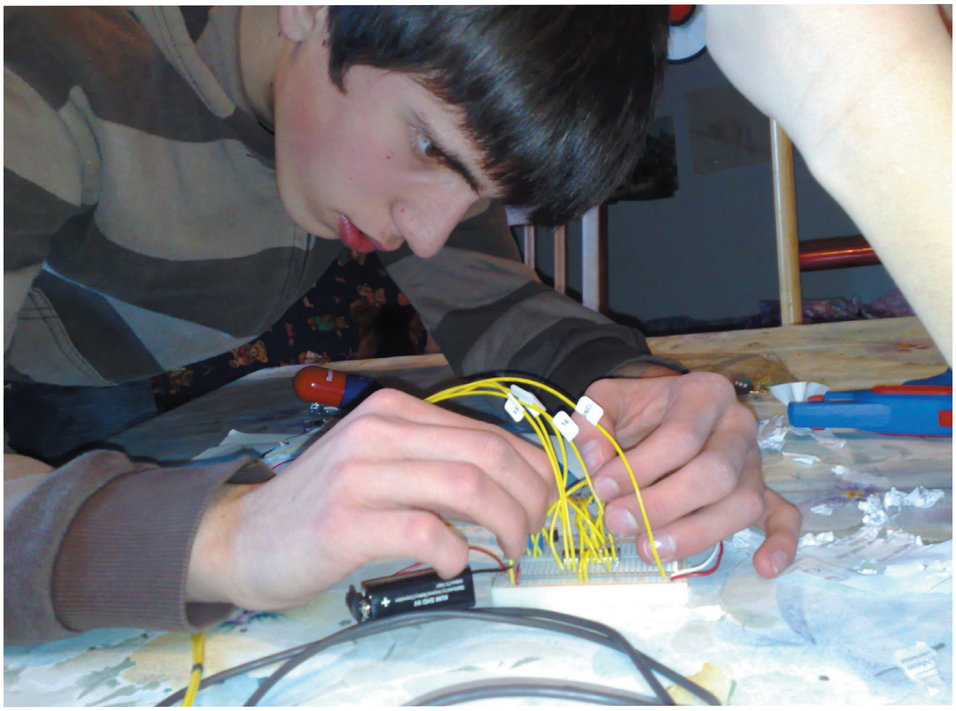
Separation of amorphous crystalline silica nanoparticles.
Credit: NIST, ScienceDaily.com

Electronics Experience for Global Education

Humberto Evans and Michael F. Robbins

Every year, the world spawns more and more Linux hackers. The open source and free software movements, combined with the widespread availability of computers and the Internet have created an environment where twelve year olds can open an online tutorial and have a "Hello World" app in minutes. More and more popular services like Facebook and iGoogle are turning into "platforms" on which anyone can become a developer. The result is an army of millions of coders who are young, passionate about technology, and find themselves with more and more venues through which to develop their talents. All of this led to major advancements in the computing world over the course of a few years. There now exist open source software to rival most professionally available proprietary software. Among The Gimp, OpenOffice, VLC, Firefox, and Thunderbird, you have a fully functional open source desktop. Even more astounding is that nowadays, you don't have to spend days setting up a working Linux machine. New distributions like Ubuntu have developed a point-and-click install. User interfaces are getting better and better; some might even say they were bordering on being intuitive! Technologists, growing up in today's world, are in a new era where the wildest dreams of sci-fi writers are quickly becoming a reality. A person can pull out his cell phone and with a few finger swipes, check his e-mail or buy movie tickets. Unfortunately, there exists a gap in the hobbyist community between software and hardware. Take any high school kid that has compiled his own kernel; I am sure that he can tell you what a segfault is, what happens when you pipe something to /dev/null, and can maybe even make you a Web 2.0 app to track the progress of your fitness goals. But ask how the computer actually generates a 2.6 GHz clock or senses motion on a touchpad, and he will be stumped. He will be unable to tell you where and why a pull-up resistor is used, or even why everything is done in





binary in the computer science world. This would be fine if we existed in an abstract world where there was no need to interact through hardware. Unfortunately, most real people live in the real world, and almost any useful computer science technology has no choice but to interact directly in new and interesting ways.

The analog world is certainly scary, but no less intriguing to technologists than the lines of code that simulate a physics engine. A student that is hacking his X-server so that his bouncing cow screensaver stretches across his two monitors would also love to learn more about the hardware chip that is implementing those OpenGL instructions. If one told him that a modern car contains as many as 80 small computers, which control physical devices (microcontrollers), he would probably want to see some of the code that makes it all work. So then the question becomes obvious: if the line between hardware and software is quickly disappearing, why are kids not learning about hardware at a young age? If the champions of technology are companies creating innovative new devices rather than new software, why are schools teaching advanced Java and not advanced circuits? Why are we giving the next generation of engineers the impression that their creations are stuck inside the computer?

" ...the best engineers are those that deeply understand the technology on which they are building."

To tackle this issue, we formed NerdKits, where we bundle electronics parts with instructional material to create microcontroller kits for beginners. We believe the best engineers are those that deeply understand the technology on which they are building. Every Linux hacker out there should not be afraid to build a circuit that turns on an LED. Whether future engineers will be developing new medical instruments for more efficient healthcare, creating control systems for cars and planes that pilot themselves, or augmenting reality with digital data, we believe the future of technology will continue to be converging the digital and physical domains, thus we aim to put this technology in the hands of anybody that is interested.

For the uninitiated, a significant problem with microcontrollers is the relatively steep learning curve. Sure, you can purchase an $8 microcontroller, and you can even get one that has a compiler for a language you know. But when it arrives, it comes with a 100 page datasheet full of circuit diagrams, and even scarier looking timing diagrams. (Non-sequential logic? Oh my!) The average person trying to tackle some project will most likely get as far as setting the fuses on the chip before putting the whole thing away out of frustration. Even if one gets as far as writing the code, the nuances of dealing with hardware registers, read/write bits, and timing will drive many software engineers crazy. So even as people become more and more comfortable with programming, the science of electronics will remain a dark art. At NerdKits, we aim to soften the learning curve by providing step-by-step, easy to understand projects, with explanations about why things are done the way they are. Moreover, we try to provide the intuition behind the concepts so that the user is ready to take on their own projects when they are ready. Our kits provide users with “the real thing,” which are the powerful components that embedded systems engineers have been using for years. Users will utilize a solderless breadboard, so that they are not locked to any fixed design on a printed circuit board, and that the components can be reused and reintegrated to tackle larger projects as the user’s skill level increases. Most importantly, we are always available to answer email support requests from our customers, because we have discovered that when learning about microcontrollers, the most essential tool is a teacher with the experience to predict which of a dozen possible failures may have taken place.

NerdKits started at Zeta Beta Tau, our fraternity house at MIT, when the common freezer broke. We took it apart to discover that the mechanical thermostat was broken, but otherwise the freezer was working fine. We decided we could fix this using a microcontroller, a simple temperature sensor chip, and a relay. After a few days, the freezer was up and running! It even had an LCD that displayed the live temperature, and would beep whenever the ice cream was in danger of melting. As we worked, we noticed a curiously high number of computer science and mechanical engineering majors that kept gathering around, excited about what we were doing. Everybody thought it was really cool, but nobody thought they could do it. That's when we started talking about building a starter kit for microcontrollers: an all-inclusive kit that would guide you through a full project step by step, and then give you direction toward future projects. We did not want to spoon-feed anyone a cool science fair project; we wanted to provide the tools to design and build new systems. After we assembled the kit and all the educational material, we shipped our first kit in November 2007. Ever since then, we have been adding new projects and filming videos about the technical concepts and project ideas.

One of the goals behind NerdKits is to get kids excited about electronics, thus we were ecstatic when a college student studying at the Technical University of Vienna, Austria, emailed us, asking for a kit that he could use with kids at his church group. We sent the kit, and soon received an email detailing all the fun they had with the kit:

"[There] were eight kids, from 6-13 years old. They had never seen something like this before and were very excited. I started to tell them something about fundamentals like what is a microprocessor good for and what signals does it use. What they really liked was the binary system. It took some minutes until they really understood, but then they started calculating their age and the time into the binary system. That was really funny. I think some of them are better now than many of my electronics classmates."

This story, along with the photos displayed, has reinforced our belief that electronics can be learned and enjoyed by people of all ages. With any luck, one of these kids will go on to develop the next great biomedical device, energy efficiency solution, or consumer electronics product.

As the MIT OpenCourseWare website states, "MIT is committed to advancing education and discovery through knowledge open to everyone." As MIT students, we have an obligation to uphold that mission by educating in a way that will benefit the nation and the world in the 21st century. We hope to break down the barriers to entry in electronics, and help reignite the spirit of the hobbyist tinkering in the garage. While we are just EECS students pursuing what we do best, we can only imagine what will happen once other science and engineering disciplines start to follow a similar pattern, expanding their community of participants.

Humberto and Michael are seniors in Course VI and continue to develop the NerdKits offerings. More information and videos can be found at http://www.nerdkits.com/.

Balancing Act

MIT undergraduates team up with high schools to create a DIY self-balancing scooter

Shane Colton

During the summer and early fall of 2007, a team of MIT undergraduates and high school students, sponsored by The Edgerton Center[1], took on the purely-for-fun engineering project of creating a self-balancing electric scooter similar to the Segway® Personal Transporter. The group, a mix of MIT mentors and students from local FIRST (For Inspiration and Recognition of Science and Technology[2]) Robotics teams, designed and built the scooter from inexpensive and lightweight components common in the FIRST kit. The finished vehicle, weighing only 53 lbs, uses sensors and simple feedback control to balance on its two wheels while a rider maneuvers it by leaning his or her body weight in the desired direction of travel. Figure 1 shows the scooter in action.

The Segway®, invented by Dean Kamen and first unveiled in 2001, has become iconic among the tech-savvy and has spawned a handful of copy-cat endeavors (none for profit, of course) in the hobby engineering world. Most famously, roboticist and Harvard alumnus Trevor Blackwell created one in 2002 that made headlines while the Segway® was still a very new phenomenon[3]. Though they are certainly less expensive, none of the imitators can claim to match the comfort, safety, and reliability of the real thing. However, they all showcase the creativity and engineering ambition of their designers. (See the references section for web links to other self-balancing projects, past and present [4]).

Figure 1: The scooter self-balancing near Lobby 10, with rider Shane Colton.

The students involved, from the FIRST Robotics teams of Cambridge Rindge and Latin School, Wayland High School, and the John D. O'Bryant School of Math and Science[5], had worked together before. The team members hatched the idea of building their own do-it-yourself self-balancing scooter during the 2007 FIRST Championship Event in Atlanta, Georgia. A venue more conducive to engineering and science enthusiasm would be difficult to find: the FIRST program, founded by none other than Dean Kamen in 1989, engages more than 100,000 students in robotic competitions each year and the Championship, held in the Georgia Dome and Georgia World Congress Center, is the culminating event of the FIRST season. Inspired by the many Segway® Personal Transporters zipping around at the event and by a homemade model created by one team (Lightning Robotics, Team 862[6]), the MIT-hosted team quickly converged on its summer project. The final decision was between a self-balancing scooter and an interactive water fountain. But as a team member astutely pointed out, "you can't ride a fountain."

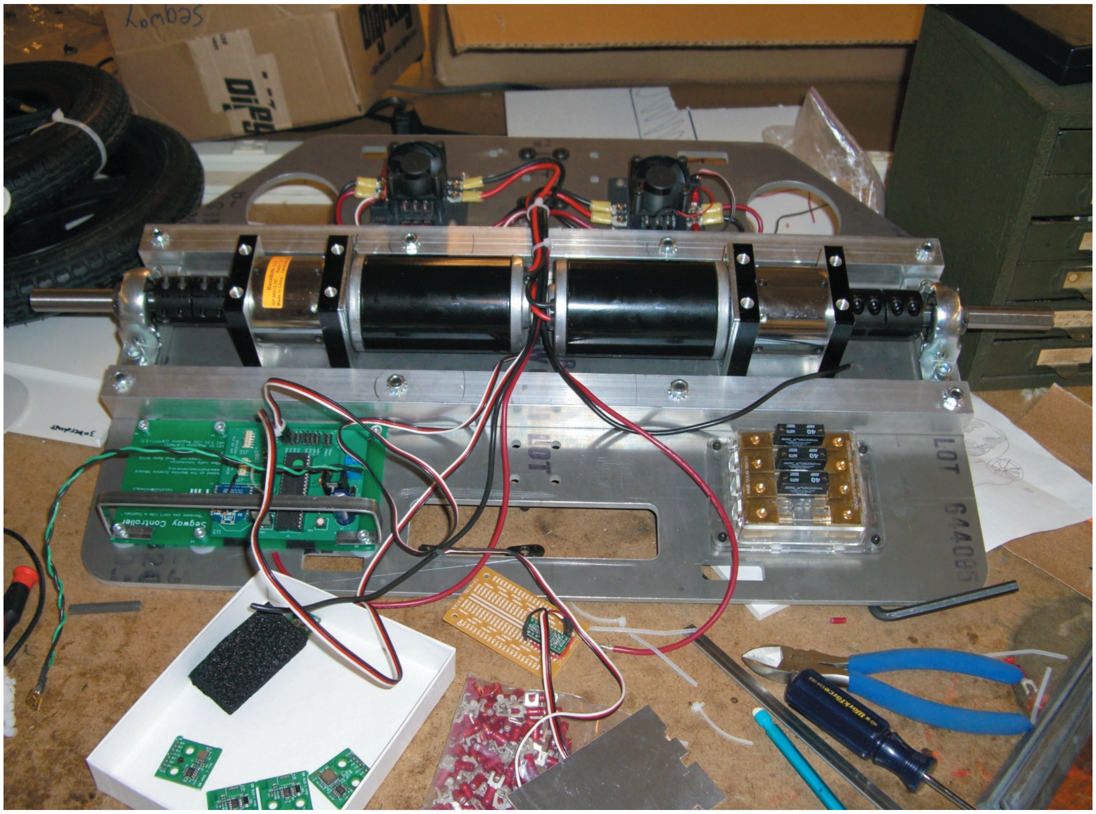


Figure 2: The base of the scooter, with motors and gearboxes in place, plus some of the control board. The sensors were still in the box (lower left) at this point.

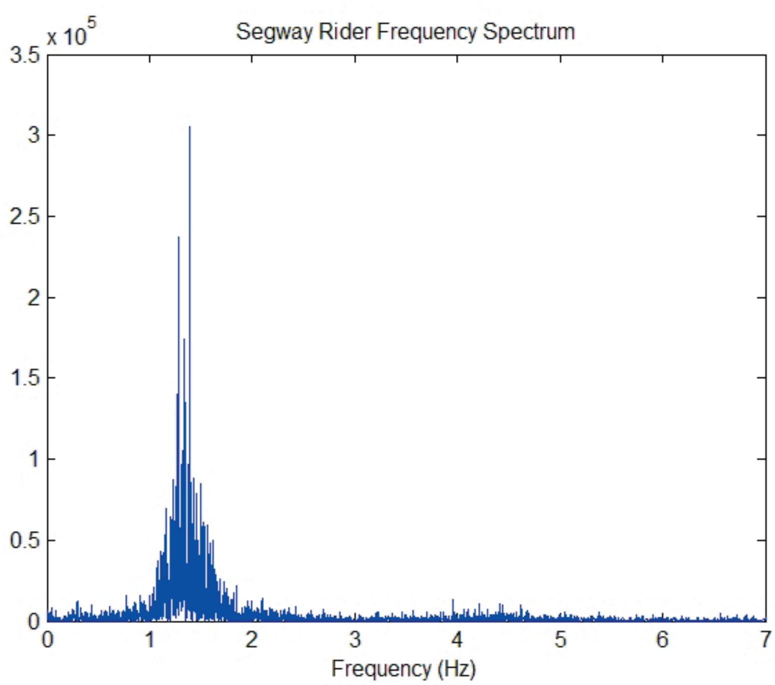


Figure 3: The scooter's data collection abilities make it possible to analyze performance wirelessly. It seems new riders have a tendency to oscillate at 1.3Hz.

Since this type of project had been done before, the team spent considerable design effort during the summer making sure that its version would differentiate itself from homemade self-balancing scooters of the past. They set an early goal of making a lighter, more streamlined, and cleaner-looking version than others, targeting a vehicle weighing about 50 lbs with the battery, narrow enough to drive easily through doors and having a clean, finished look. The team also wanted to replicate a feature of the most recent Segway® model that allows the rider to steer by simply leaning the handlebar rather than using a twist knob or joystick. Since it would be used as an educational tool, a very simple sensor and software approach was also an important design target. All of this needed to be accomplished on a budget of about $1,000.

Toward the size and weight goals, the team built the vehicle chassis around a 1/4" aluminum plate cut on the abrasive water jet at the MIT Hobby Shop[7]. Rather than using powerful but bulky wheelchair motors common on similar projects, their DIY version utilizes the inexpensive and lightweight DC motors and planetary gearboxes featured in the 2007 FIRST kit. The motors generate a maximum of 343W of power each, giving the scooter a total of just under one horsepower. The planetary gearboxes provide a 16:1 gear reduction to increase the torque output to the wheels, which are 12.5" in diameter with pneumatic tires and composite hubs. The handlebar, cut from aluminum extrusion, is hinged to allow for steering control. Figure 2 shows the base of the scooter, nearly finished at the time.

> "...its simplicity and low cost has helped inspired a new wave of self-balancing projects and the team has received feedback and new project links from around the world.."

To achieve self-balancing, the scooter implements a feedback control system. It senses both the angle of the base platform and its rate of angular rotation, feeding a combination of these values back into the motor controllers to create a corrective action. For example, if the rider begins to lean forward, the sensors will detect the lean and the control system will send a command to the motors to drive forward, bringing the base back under the rider's center of gravity and "catching" the fall. The command sent to the motors is proportional to both the sensed angle and the angular rate of the platform, a scheme known as PD (Proportional + Derivative) control.

The sensors are small, inexpensive MEMS accelerometers and gyroscopes (angular rate sensors) made by Analog Devices. One accelerometer, used to sense the angle of gravitational force and one gyroscope are used to estimate the angle (with respect to horizontal) and the angular rate of the base platform. A second accelerometer is used to detect the angle of the handlebar for steering. A problem that almost every self-balancing project write-up mentions is the difficulty of obtaining an estimate of angle from the noisy accelerometer signal and the integrated angular rate signal, which drifts over time. The team overcame this problem with a very simple digital filtering technique called a complementary filter, forgoing more complex and computationally-intensive methods such as Kalman filtering for an effective and intuitive solution. The details of the filtering and control algorithm can be found in the project's full technical documentation[8].

The control computation is done on an on-board microprocessor. Though the circuit board was custom-designed, it is based on a PIC microcontroller starter kit developed by Machine Science[9], a local non-profit organization promoting hands-on engineering education. The kit and online development environment were simple to use, but powerful enough to execute floating-point (decimal) filtering and control calculations. The main software loop, which reads and filters the sensor inputs, calculates the corrective action, and generates a signal for the motor controllers, runs at 100Hz, fast enough to stabilize the vehicle's mechanical dynamics.

Development was also streamlined by a custom wireless programming and debugging interface that allowed the team to modify software and view sensor values in real-time with no physical connection to the vehicle. Data can be viewed and collected remotely from up to 300 feet away while a rider is cruising on the scooter, a feature that increases the educational value of the project and which the team believes is unique to its version. Figure 3 shows an example of the wireless data collection capabilities, a frequency analysis of the natural oscillation of riders over the course of a 40-minute demonstration session.

The project concluded in the late summer and early fall of 2007, just in time to allow the designers to get back to schoolwork. Since it was finished, the team's self-balancing scooter has been featured on several prominent technology blogs, including Engadget[10], Gizmodo[11], and MAKE[12]. Its simplicity and low cost has helped inspired a new wave of self-balancing projects[13] and the team has received feedback and new project links from around the world.

Pictures and video of the scooter in action can be found on the project website: http://web.mit.edu/first/segway. The scooter will also be on display at the Edgerton Center "Cool Project Open-House" during CPW, the 2.007 Final Contest on May 8, and orientation in the fall. To contact the team directly, email seg-info@mit.edu.

References

1 http://web.mit.edu/edgerton/main.html

2 http://www.usfirst.org/

3 Blackwell T. Building a Balancing Scooter. http://www.tlb.org/scooter.html. 2002. Accessed 2008.

4 Other examples of self-balancing projects:

A one-wheeled skateboard version: http://www.ben.jellybaby.net/

An autonomous robot: http://www.geology.smu.edu/~dpa-www/robo/nbot/

Done with Lego®: http://www.teamhassenplug.org/robots/legway/

5 Links to the teams' or schools' web sites:

Team 97, Cambridge Rindge and Latin School: http://web.mit.edu/first/www

Team 2349, Wayland High School: http://www.waylandfirst.com

The John D. O'Bryant School of Math and Science: http://obryant.us

6 http://lightningrobotics.com/forum/portal.php

7 http://hobbyshop.mit.edu/

8 Technical documentation files, including design notes, drawings, filter and control algorithm explanation, and source code, available at: http://web.mit.edu/first/segway/segspecs.zip

9 http://www.machinescience.org/

10 http://www.engadget.com/2007/08/21/clever-students-create-cheapo-diy-segway/

11 http://gizmodo.com/gadgets/segway_hey%21/diy-segway-looks-like-modded-golf-caddy-291140.php

12 http://blog.makezine.com/archive/2007/08/diy_segway.html

13 Examples of recent self-balancing projects from the web:

http://segskate.googlepages.com/

http://cobweb.ecn.purdue.edu/~477grp12/index.html

Developing World Prosthetics

A majority of the world's disabled people live in the developing world. Despite this fact, technological improvements are still geared toward a minority of patients that can afford high-end devices. We are working to make technological advances while operating under the conditions that are prevalent in most of the developing world.

Maria Luckyanova and Melis Anahtar

Developing World Prosthetics (DWP) is a non-profit organization dedicated to the design and deployment of prosthetic limbs, orthotic braces, mobility aids, and fitment devices for patients in developing nations. In collaboration with the Indian non-profit Jaipur Foot Organization (JFO), which has fit over 250,000 lower-limb prosthetics, and other multinational rehabilitation organizations, we are increasing the number and quality of low-cost, specialized mobility devices that are specifically designed to maximize patient throughput. As an MIT spinoff organization, we hope to use our strong connection with the Institute and its engineering students, classes, and facilities as a means of deploying appropriate medical technologies.

Our Origins as Vac-Cast Prosthetics

In the spring semester of 2007, Vac-Cast prosthetics, a team of MIT students and future founders of DWP developed a low-cost, portable, human-powered vacuum device that enabled the JFO to implement a highly-sought rapid prosthetic fitment technique in rural fitment camps through Indochina. The JFO offers a free prosthetic fitting and forming service through 16 urban centers across India and dozens of mobile fitment camps that reach out to particularly remote villages or crisis areas. Though the mobile camps are the only recourse for those patients who are unable to reach urban medical centers, tight operating costs and limited resources constrict camp deployment to no more than three weeks at a time. In order to reduce the material costs and to increase the patient throughput of mobile camps in rural areas, the JFO and Dr. Yeongchi Wu of the Center for International Rehabilitation (CIR) in Chicago co-developed a rapid prosthetic fitting process that utilizes renewable material resources and advanced cast-forming technology. Despite granting a cost reduction in fitting materials, the new high-throughput prosthetic fitting technology also requires the use of an air compressor and subsequently introduces the greater cost of renting, fueling, and maintaining an electric generator used to power the air compressor. Vac-Cast improved upon the rapid prosthetics forming technology by inventing a human-powered vacuum pump that eliminated the need for an electric generator in mobile fitment camps that sought to employ the rapid fitting process.

Team Vac-Cast included four MIT undergraduate students and one PhD student from the Mechanical Engineering Department, as well as a former MIT student from the Electrical Engineering department. In early May of 2007, the team won the Lemelson-MIT award at the IDEAS competition. Part of the funds from the award were invested in creating further generations of a primary prototype of the Vac-Cast system.

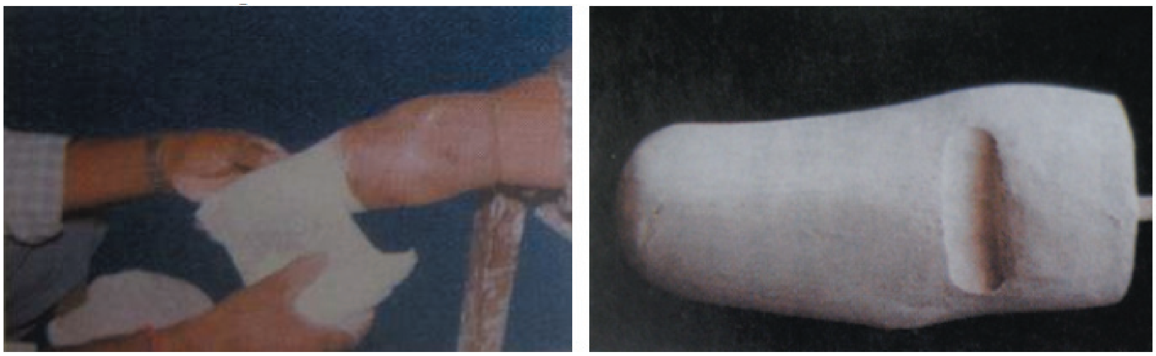


Figure 1: This is the standard plaster method. The POP technique, currently used in rural fitment camps, requires several hours of preparation of the residual limb, heavy involvement of a prosthetist in creating the POP cast, and several hours of waiting for the positive mold to set before a thermoformed socket can be made. There is also a large amount of waste created from the completed positive mold of the residual limb, made entirely of solid POP.

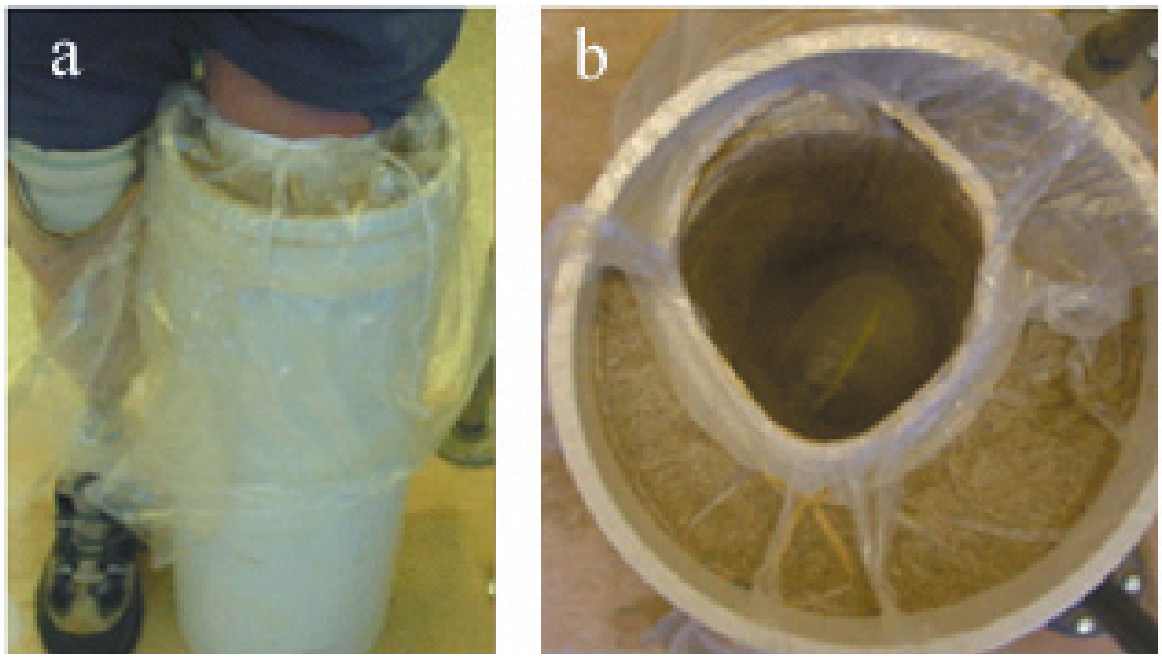


Figure 2: (a) An amputee putting his residual limb into the vat of sand from which a negative mold will be cast and (b) a negative mold of the amputee's residual limb using vacuum sand-casting. This negative mold is then filled with sand, and a vacuum is drawn on this sand. This created an exact replica of the residual limb.

The Technology

The traditional method for producing an artificial leg requires an expendable plaster intermediate (fig. 1). Explicitly, a plaster negative cast of the residual limb is filled with more plaster to make a replica of the socket. Once the plaster positive cast is dry, it is altered by orthotists/prosthetists (O&Ps) to tailor the mold to the patient's particular anatomy. For example, bony protrusions and scar tissue are evident on the cast, but cannot bear a load. A heated, malleable, skin-colored PVC pipe is formed over the dried and modified plaster replica. The custom-fitted prosthetic is then ready to be worn.

There are two main problems with this process. The first is that plaster expands when it dries, making the plaster replica slightly bigger than the amputees' actual residual limb. Thus, the final PVC prosthetic socket may also be too big, and patients must wear multiple socks to compensate. The second problem is waste; even though plaster is cheap, it is also unrecoverable, so molds are just thrown away after each fitting.

The Vac-Cast system solves these two problems by applying the process of vacuum sand casting (SC), which was pioneered by Dr. Yeongchi Wu of the Center for International Rehabilitation. With SC, an amputee places his residual limb into a sealed vat of sand, over which a vacuum is drawn. Through the dilatancy principle, the sand maintains a rigid negative mold (fig. 2). A positive sand cast of the residual limb can then be made by pouring sand into the negative cavity and drawing vacuum on the positive cast through a mandrel (tube).

Figure 3: Two DWP team members test the Vac-Cast vacuum-forming device in a JFO clinic in Jaipur, India in January of 2008.

In less than a minute, a positive sand cast of the residual limb can be manufactured, and then tailored to the patient by an O&P and used to thermoform a prosthetic socket that is more accurate than those made from POP molds. The entire SC process, from residual limb preparation to fitting the prosthetic into the thermoformed socket, takes only one fifth the time required for the POP method. The critical component of this forming process is the vacuum-forming device. Vac-Cast eliminates the need to rent, fuel, and operate a generator to create the vacuum, using simple components like bike pumps, gears, timing belts, and one-way valves to rapidly and manually generate a vacuum and evacuate air.

Work in India to Date

In August of 2007 and January of 2008, members of the Vac-Cast Prosthetics team traveled to Delhi and Jaipur, where two of the JFO's biggest urban fitment centers are located (fig. 3). They received feedback and further design parameters for the Vac-Cast vacuum system, learned about the fitment process, and generated new project ideas to improve the patient care the organization provides. They demonstrated the device both for practicing orthotists/ prosthetists (O&Ps), and for JFO representatives who work primarily on research and development.

While working at the clinics with patients, doctors, researchers, and students, the team learned about patient care, the available manufacturing materials, and JFO's resource and time constraints. This experience revealed not only the problems with the Vac-Cast system, but those of other devices and techniques the JFO uses. Due to time constraints and the great number of patients that must be seen every day, most of the O&Ps do not have time to improve on technologies

> "Vac-Cast eliminates the need to rent, fuel, and operate a generator to create the vacuum, using simple components like bike pumps"

Figure 4: Current prosthetic knee technology does not allow a normal gait or normal muscle control.

for better treatment of their patients. On the other hand, due to their extensive first-hand experience, they have the clearest view of how patient care is hindered, and where improvements are most necessary.

DWP extended offers to assist the JFO in developing technology and improving their devices to help them administer the best patient care. They left India having established strong personal and professional connections. These ties provide an exciting opportunity for MIT to work with the JFO to be on the cutting edge in devising medical care solutions that both improve quality of life for millions of people and respect the limited resources available in the developing world.

Future Projects

The JFO focuses on patient care, but its intimate knowledge of both the available resources and the needs of the patients makes it best suited to develop project ideas that would be most helpful in the realm of mobility aids for the developing world. The time spent collaborating with the JFO in India resulted in a list of needs that O&Ps at the JFO want to address and potential products for MIT students to engineer. This list includes perfecting the sandcasting system that is currently under trial and improving mobility devices themselves. For example, the JFO wants to improve orthotic knees for polio patients and to create stance-control orthotic and prosthetic knees for above-knee amputees (fig. 4). Current low-cost technologies do not allow patients to bend their knees for a normal gait. Instead, above-knee amputees walk with a straight-legged gait and activate a mechanism that allows them to bend the knee when they want to sit. It is imperative to further mobilize these patients, while increasing comfort and maintaining normal muscle control. This is a problem currently being tackled with a rehabilitative devices seminar running this spring under the Edgerton Center.

Rehabilitation Class at MIT

SP.714, Engineering Rehabilitative Devices, engages the collective energies of MIT students from a number of disciplines in improving mobility aids and rehabilitative technologies in the developing world. Many noted individuals in the rehabilitative field are guest lecturers for the course, including Dr. Hugh Herr of the MIT Media Lab, Dr. Yeongchen Wu of the CIR, Dr. Bob Emerson, a private O&P from the Boston area, and Mr. Sanjeev Kumar, one of DWP's primary contacts from the JFO in Delhi. The aim of the class is twofold: to provide a broad knowledge base about rehabilitation and to apply this knowledge to the completion of a project. Through the class, students will learn about devices on the forefront of prosthetic technology and on the mass-manufactured devices used for the majority of patients in the developing world. There is a parallel goal to teach students about the biomechanics of walking to contextualize the technology they are learning about. The second goal of the class is for the students to complete some of the projects that the JFO does not have the resources to work on, as previously outlined. This class is one of a new collection of classes under the umbrella of M-Lab, or Mobility Lab, a D-Lab spinoff. By becoming a permanent fixture at MIT, students in the class can continue helping the JFO and other partner organizations promoting service learning at MIT, and strengthening MIT's impact on the developing world.

The Developing World Prosthetics team is comprised of undergraduates Philip Garcia, Maria Luckyanova, Jessica Shirmer, and Tess Veuthey, and graduate student Goutam Reddy. More information on SP.714 can be found at http://web.mit.edu/sp.714/www/Home.html.

EECS is Everywhere

Paul Baranay

Professor Eric Grimson, head of MIT's Electrical Engineering and Computer Science (EECS) Department, speaks to MURJ about research, finding balance, and the future of computer science.

When asked about how he finds balance in his life, Professor Grimson's first response was a thoughtful, "That's certainly a good question." Just like students, Grimson said, faculty can struggle to strike the best balance between their professional and personal lives. "If the physicists ever come up with those extra two hours a day they've been promising us, I'll be very happy." Until that happens, though, Grimson explained that he frequently shifts his priorities—which range from his responsibilities to his students, to his research commitments, to his administrative duties—depending on what he believes to be most important.

Prof. Grimson briefly outlined some of his goals as the head of MIT's largest academic department. While "it's easy to say, 'Why mess with [the top-ranked EECS program in the country],'" Grimson asserted that Course 6 does have room for improvement, affirming his belief that the new curricular changes are being implemented in order to help EECS at MIT "make a better experience" for Course 6 students. Although Grimson did not hide that he still enjoyed the popular 6.001 class (Structure and Implementation of Computer Programs)—which he personally taught roughly thirty times and whose evolution he carefully monitored in order to "build a course I was really happy with"—Grimson express his optimism that the new Course 6 curriculum would be a catalyst enabling MIT's EECS department to truly "move to the next level."

Although he has researched "a lot of different things," Grimson mentioned that he was happiest with his work on image-guided surgery, because it is "something you know makes an impact." Grimson added that he feels many current MIT students also are deeply committed to positively improving others' lives through their research.

In a similar vein, Prof. Grimson has also been conducting research employing "computational anatomy" as a new tool to determine the correlations between neurological diseases and brain structure. Such research, he explained, seeks to discover if individuals with neurological disorders—such as schizophrenia, Alzheimer's, bipolar, and fetal alcohol syndrome, among others—actually possess statistically different parts of the brain, compared to controls. Although neurological disorders represent a very promising avenue of study, Dr. Grimson did state that a similar principle could also be applied to other diseases.

To wrap up our discussion of his personal research, Prof. Grimson mentioned some of his lab's work on creating computerized security and vision systems. These systems help security personnel categorize activities and behaviors in an anonymous fashion, which is "deliberately set up so we can't identify individuals but can learn standard behaviors" for a particular site, such as a park or airport. The technologies developed in Dr. Grimson's lab have already been installed at various ports and even MIT's own Lincoln Lab. Grimson stressed that ethical behavior and privacy were two key concerns of any projects he undertook relating to public safety. He also emphasized that he saw artificial intelligence systems as "amplifiers," not substitutes for actual humans.

Next, Prof. Grimson was asked what he believed was the most important quality necessary for undergraduates seeking to conduct research. Without hesitation, Dr. Grimson answered, "Fearlessness." He explained that, in order to conduct great research, students needed to be "willing to tackle problems where you don't know the answer… you've got to be willing to crash and burn, to throw your results away after three weeks [if they're not working], to go out and get the tools you need. You can't let your ego get in the way." Grimson praised UROP as a program that "distinguishes us from so many other institutions," emphasizing that UROP helps provide students with transferrable skills and challenge them to "think analytically, to problem solve…in multiple domains." This, Grimson explained, is part of why MIT alumni are "prepared for almost any career."

"...students need to be willing to tackle problems where you don't know the answer…you've got to be willing to crash and burn... You can't let your ego get in the way."

Grimson said that he would like to see more students and faculty alike finding the time to "take a deep breath…to think those great thoughts"—even about things as seemingly cliché as, "Where do I want to be two years from now?" Dr. Grimson further explained that taking time away from one's work, besides giving one room to breathe, also had the very practical effect of enabling one to gain perspective on tough problems—noting that "answers are not always in the lab." Grimson explained that he inherited this mindset from his own supervisors when he was a student, as they frequently challenged him to "go take a walk, get out of that grind…"

Last, but certainly not least, Prof. Grimson talked briefly about the future of EECS, both within MIT and around the world. "It's a really hard question," he said—"I wouldn't want to pick a particular area [to focus on]." Fundamentally, Grimson said, "EECS is everywhere. And that's not just a slogan. Our mode of thinking is important everywhere and going to spread more and more." Grimson called EECS "the liberal arts of engineering," explaining that it was relevant for "Wall Street, bioinformatics," and many other fields. Above all, Grimson expects that we will see "EECS modes of thinking becoming even more prevalent in the future."

Dr. Eric Grimson is head of the Department of Electrical Engineering and Computer Science—also known as Course 6, MIT's largest academic department. Dr. Grimson holds the Bernard Gordon Chair of Medical Engineering at MIT and earned his Ph.D. in mathematics from the Institute in 1980. Professor Grimson, a Fellow of the American Association for Artificial Intelligence and a Fellow of the Institute of Electrical and Electronics Engineers, was awarded MIT's Bose Award for Excellence in Teaching in the School of Engineering in 2011.

UROP Summaries

Photovoltaic Devices as Renewable Sources of Energy
Spring 2008
Department of Electrical Engineering and Computer Science
Soft Semiconductor Group
Principal Investigator: Professor Marc Baldo
Supervisor: Tim Heidel

Nasly Jimenez, Class of 2009

Major: Chemical Engineering

Creating better ways to harness renewable sources of energy, such as the Sun, is a growing concern in today's energy-conscious society. Silicon solar cells, the predominant solar energy technology currently in use, utilize crystallized material that is expensive and inflexible, making the cost of using solar energy to harness electricity high. At MIT, the Soft Semiconductor group, led by Professor Baldo, has undertaken research to create solar cells utilizing organic electronic materials. Using organic or photosynthetetic molecules, instead of the crystalline silicon, could potentially reduce the cost of using solar energy. One of the main challenges facing organic solar cells today lies in absorbing enough light. Photo-generated excitons can only travel so far before recombining in organic solar cells. Therefore, the devices can only be made so thick without sacrificing efficiency. Unfortunately, this limits the amount of light that can be absorbed in the solar cells.

One idea for improving efficiency is to build the solar cells inside a microcavity. Electrical Engineering and Computer Science graduate student Tim Heidel is investigating this possibility by creating cavity devices. The devices are designed to absorb light very strongly over a specific range of wavelengths. The cavity devices are characterized by the semiconductor layers fabricated between semi-transparent and reflecting silver layers that improve the overall absorption of light within the devices. Ultimately, devices tuned to different regions of the solar spectrum will be connected together so that they can absorb sunlight throughout the visible spectrum.

I will be working directly with Tim Heidel to fabricate cavity organic photovoltaic devices using a thermal evaporator. I will fabricate cavity devices tuned to different wavelength ranges by varying the semiconductor material as well as the thickness of each layer. The work will be performed in a class 10,000 clean room maintained by the Soft Semiconductor Group in Building 13. I will also be responsible for testing the devices using a solar simulator, a light source that emits light matching the solar spectrum. Devices will be tested in darkness and under illumination. By analyzing the generated I-V curve we can calculate the power efficiency of each device. Further investigation may arise from results, as well as side projects that are related to creating organic solar cells. The time commitment will average about six hours a week and will vary as necessary.

Feedback Control Loop for the Hydraulic External Pre-Isolation (HEPI) System
June 2007- Present
Department of Physics
Laser Interferometer Gravitational-wave Observatory (LIGO)
Principal Investigator: LIGO Scientific Collaboration
Supervisor: Richard Mittleman

Sharon Rapoport, Class of 2010

Major: Physics

Because they carry information without being interrupted, gravitational waves can teach us about the merging of black holes, neutron binary systems, and possibly even about the creation of the universe. Since gravitational wave's polarization varies, these waves can be detected with an interferometer. When a gravitational wave passes through the interferometer, it stretches one of its arms while shrinking the other. For the predicted gravitational waves which can hit the earth, the strain amplitude $\lambda = \Delta L/L \approx 10^{-21}$. Long cavity arms are preferred, as this makes the change in arm length much easier to detect.

The Laser Interferometer Gravitational-wave Observatory (LIGO)'s equipment is based on the Michelson interferometer with two perpendicular arm cavities and a power recycling mechanism. The laser goes through a beam splitter, separating it into the two cavities. The beam's power is then amplified using mirrors along the cavities. These mirrors are connected to a test mass mounted to a pendulum. After being amplified, the beams recombine and the signal is detected. If the two cavities have the same length, the beams will return with opposite phases and will destructively interfere with each other, causing a resultant signal output of zero. However, if agravitational wave does change the lengths of its arms, the phases will no longer destructively interfere and a signal can be detected. This signal can be attributed to the change in space-time. The LIGO detector is extremely sensitive and can even detect a falling tree. The noises that interfere with the detected signal are divided into 3 groups: seismic noise, thermal noise, and photon shot noise. Seismic noises, which can be created by earth vibrations, ocean tides, cars, and even planes, are particularly critical between 0.1 to 10 Hz. The thermal noise, which is currently the most problematic, is caused by molecular motion associated with non-zero temperature and governs the range of 30 to 150 Hz (Santamore and Levin, 2007).

The Hydraulic External Pre-Isolation (HEPI) system is used for seismic isolation and is required for keeping the arms locked in space when data are being recorded. Therefore, we are working on improving the isolation from HEPI by upgrading the filters that control it. Controlling means applying filters in a feedback control loop which will make constant and immediate corrections for the movements of the HEPI system.

In order to improve the isolation, we learned the behavior of HEPI by applying force on the system and taking the transfer functions of the sensors. Once we collected all the data, we eliminated the unstable reads using filters. Since we understood the mechanical properties of the system, we recognized their influence in the transfer functions and used filters to correct our data.

The HEPI includes four horizontal sensors and four vertical sensors. After reducing the noise from each sensor, we combined the eight sensors to receive an indication in the modal form, which shows the movement in each degree of freedom. We tested the efficiency of the filters when applied separately on each sensor and when applied in the modal form, finding the modal form correction to be more precise. Now we are rearranging the supporting software to suit filters in the modal form. Once the software is ready and the filters are loaded, we will be ready to run the system and observe its new behavior. As the transfer functions indicate improvement to data collection, the new filters can be incorporated into LIGO.

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Characterization of Near-Earth Asteroids Using Near-Infrared Reflectance Spectroscopy

Spring 2007 – Present
MIT Planetary Spectroscopy Laboratory
Department of Earth, Atmospheric, and Planetary Sciences
Principle Investigator: Richard P. Binzel

Shaye Storm, Class of 2008

Major: Earth, Atmospheric, and Planetary Sciences

We observe Near-Earth asteroids (NEAs) using NASA's Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. We are interested in NEAs because of their proximity to the Earth (within 1.3 AU). Their orbit creates the potential to hit the Earth and we want to characterize the physical properties of the bodies to understand the consequences of a potential impact. Although the IRTF is located on the Hawaiian summit, our group uses it remotely from our offices in Building 54 at MIT.

The telescope is equipped with a medium resolution spectrograph and imager called SpeX [1], which allows us to observe the reflectance spectra of asteroids at near-infrared wavelengths ranging from 0.8 - 2.5 μm. This wavelength range captures two very important absorption bands that are crucial for studying the mineralogical properties of asteroids. The raw astronomical exposures we obtain from SpeX require a great deal of processing to extract the true signal from the asteroids. I am in charge of reducing the raw spectral data for each observation and producing the final asteroid spectra.

Reflectance spectroscopy of asteroids is also used to understand the formation and evolution of the Solar System. Current unsolved problems in Planetary Astronomy include finding the source asteroids for the meteorites we find on Earth, figuring out what part of the main belt fuels the NEA population, and understanding physical and thermal trends in the main asteroid belt that can help us understand the overall cosmochemistry of the Solar System. These are all questions that are being pursued by our group at MIT.

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Tissue and Organ Development

Spring 2008- Present
Harvard-MIT Division of Health Sciences and Technology
Principal Investigator: Syed Hasan, Postdoctoral Fellow
Supervisor: Utkan Demirci

Anna Dikina, Class of 2011

Research being conducted in Dr. Syed Hasan's laboratory focuses on tissue and organ development. The need for replacement tissues and vasculatures has driven the research for constructing these in the laboratory. This group is attempting to manually develop two- and three-dimensional structures of a variety of organs—from bladder, arteries, and veins comprised of smooth muscle; to the heart, consisting of cardiac muscle—that will be eventually transplanted into animal models. Cell printing techniques, either by hand or automated cell ejection, are the basis for this project. Currently the research is in the early steps of attempting to successfully and consistently produce tissue by incubating the printed mouse bladder cells submerged in medium.

I will be researching in lab 252 at the HST/BAMM building on 65 Lansdowne Street, Cambridge. I intend to work for fifteen hours per week, including one seven-hour and two four-hour sessions. My primary responsibility for this project will be to print cardiac muscle tissue.

My role will concentrate on detailed development of cardiac muscle tissue. I will prepare collagen to allow for cell survival. I will manually and by the means of a cell ejector print cells into tissue. I will monitor their growth and provide the proper conditions. I will stain printed tissues so that we will be able to more clearly view their structure under a light microscope. And I will in other ways assist Dr. Hasan in his research. During the downtime of experiments, and on my own, I will be reading literature on smooth muscle and cardiac muscle cell development, tissue formation, organ function, and other related topics. Each week, I will provide a report of the process and results of my experimentation at lab group meetings.

This project will give me an opportunity to fully explore the workings of lab research. I am majoring in Chemical-Biological Engineering (Course 10B), so this opportunity will help me decide if I wish to pursue further research in this field or if I perhaps want to "go into industry." This will be my first time working in a lab for an extended period of time, so I hope that this will help me formulate my future goals wisely. I also look forward to building valuable relationships with faculty and other UROP students, especially as Dr. Hasan's group includes three other undergraduate students. Overall, I expect this research experience to provide me with a great deal of insight into the medical research field as well as introduce me to many knowledgeable individuals.

The Role of Nuclear Reprocessing in Advancing Nuclear Energy

January 2008- Present
Department of Nuclear Science and Engineering
Advisor: Professor Andrew Kadak

Christopher M. Boyce, Class of 2011

As the world moves towards relying completely on carbon-free energy, nuclear power has the potential to become the world's major energy source. For this to occur, however, three major problems must be overcome. These important issues in nuclear engineering are effluent waste management, a lack of long-term sustainability due to limited uranium supplies, and concerns of nuclear weapons proliferation. This semester, I have been conducting research as a UROP student investigating nuclear reprocessing, which combines the fields of nuclear and chemical engineering to develop techniques that may solve the problems inhibiting nuclear energy expansion. Nuclear reprocessing technologies are being developed to chemically extract uranium and other elements from the power plant waste stream to be reused in nuclear reactors, creating a new uranium supply stream and sharply decreasing waste amounts while also minimizing the threat of plutonium proliferation. By increasing energy efficiency while decreasing waste and proliferation risks, nuclear power could represent a turning point for nuclear power to become the world's largest, safest, and most sustainable energy source.

Currently, nuclear power plants in the United States use the "once-through" nuclear fuel cycle, in which uranium fuel is fissioned in a reactor then stored on-site as waste once the reactor is shut down. Even though this spent fuel is treated as waste, it in fact still contains over 90% of the original uranium put into the reactor, representing a significant amount of discarded fuel. Additionally, leftover uranium and other actinides account for over 95% of the mass of the spent fuel, as well as a considerable amount of its long-term radioactivity. With the ongoing build-up of spent fuel, waste management storage facilities are reaching their capacities.

To remove uranium and other important elements from the waste, chemical separation and reprocessing techniques use a complex set of extraction steps. Aqueous processes, which are currently used industrially in France, dissolve spent fuel in nitric acid before using different oxidizing and reducing agents to manipulate uranium and plutonium into ideal oxidation states for extraction. Because the most common chemical extractant used, TBP (tributyl phosphate), only extracts metals in hexavalent and tetravalent oxidation states, only uranium and plutonium are removed to be reprocessed, leaving all other elements to be stored as waste. More advanced aqueous-based techniques call for using similar chemical processes to remove long-lived radioactive and heat-producing isotopes from the waste stream for separate storage. In order to dispel proliferation concerns, advanced processes would also extract a reprocessing stream of plutonium with highly radioactive neptunium.

Though aqueous processes are currently the most-developed reprocessing techniques, they do present additional problems, including the production of an excessive waste volume and a "cooling period" time delay between reactor shutdown and reprocessing. The most prominent alternate technique is pyro-processing, which chops up spent fuel metal into fuel pins and places them in a basket at the anode of an electrolytic cell. When a small voltage is applied, the metals dissolve into high-temperature molten salt. Because the voltage applied is small and the uranium ions have the highest electric potential, only uranium is deposited on the cathode, leaving all other elements to be collected in the waste stream.

My current research goal is to provide a comparative analysis between aqueous techniques and pyro-processing, since General Electric is looking to use pyro-processing industrially in the U.S., much as aqueous processes are already used overseas. My analysis will compare the economics, separation efficiencies, and technological readiness of each process to determine which is best to incorporate into the U.S. nuclear fuel cycle for the near future. Additionally, I will be researching new separation techniques for future exploration at MIT. These alternative techniques would exploit the unique properties of uranium, such as the volatility of its hydrogen fluoride compounds at high temperatures, or investigate non-aqueous solutions such as supercritical carbon dioxide. Other areas of development for research would include identifying or developing methods to separate additional elements during pyro-processing. The ultimate goal of researching different reprocessing techniques will be to extract elements efficiently in order to make nuclear energy production as economically viable and environmentally safe as possible.

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Looking for Life in the Multiverse

Spring 2007- Present
Department of Physics
MIT Center for Theoretical Physics
Principal Investigator: Prof. Robert Jaffe
Supervisor: Prof. Robert Jaffe
Collaborator: Dr. Alejandro Jenkins

Itamar Kimchi, Class of 2008

Major: Physics

The standard model of particle physics, first developed in the early 1970's, continues to reliably serve physicists today as a succinct mathematical summary of all that is known about the fundamental particles in our universe, with only small modifications. The theories in the model involve between 20 and 30 parameters, such as interaction coupling constants and fundamental particle masses and energies. No common pattern has yet been found among these dimensionless parameters, leading some physicists to question the search for a single unified theory that will uniquely determine the values of these parameters. Indeed, many new theories appear to have no unique "vacuum solution" that would correspond to our universe and instead define a "multiverse" of possible solutions, such that each region of the multiverse could potentially possess its own set of physical parameters. Operating under this framework, some physicists have suggested a possible approach to understanding our universe's fundamental parameters called the anthropic principle. The *anthropic principle* focuses on the fact that we humans are able to measure the parameters of our universe only because these parameters have created a physical environment (our universe) that is conducive to the evolution of life. It suggests that the parameters of our universe may be thought of as "selected" from a larger pool of possible parameter sets by the requirement that life exist. Critics of the anthropic principle, however, question the idea that, even if the notion of a landscape of possible universes with various parameter sets turns out to be true, this would count as an actual explanation of why the parameters of our universe are what they are.

Our project with Dr. Alejandro Jenkins and Prof. Robert Jaffe set out to explore whether it is in fact true that most of the different values of physical parameters would not permit life. Specifically, we investigated the effect of light quark masses on the spectrum of stable nuclei.

While it is impossible to predict what conditions would permit the evolution of what we would call "life," we can assume that the long-range order necessary for complex systems can only be created with electromagnetic interactions between clumps of a few charges. Therefore, as we investigated various sets of light quark mass values, our operating condition for life was that stable nuclei with a charge of at least magnitude 6 (i.e., carbon) must exist. Understanding whether charged nuclei—and therefore atoms and molecules—would be created in imaginary universes with different quark masses could rule out the use of the anthropic principle in explaining the quark mass values in our universe. More advanced physics would be necessary to explain why our universe has the quark mass values it does.

The first stage of the project entailed finding the effect of light up, down, and strange quark masses on the masses of the eight lightest nuclear particles (the octet of baryons, which includes the familiar proton and neutron that make up atomic nuclei in our universe). We performed first-order perturbation theory on the effects of breaking the SU(3) symmetry between the three up, down, and strange quarks to extract the necessary invariant matrix elements together with their SU(3) Clebsch-Gordan coefficients (similar to the familiar spin SU(2) Clebsch-Gordan coefficients) from baryon masses in our universe in order to extrapolate to different quark masses.

The second stage entailed generalizing the Weizsacker semi-empirical formula for masses of nuclei, to include nuclei constructed of all eight octet baryons with varying masses (i.e. not just the proton and neutron). To do this, we used the common model of a nucleus as a drop of noninteracting liquid under constant pressure (the degenerate Fermi gas model). We also needed to generalize the asymmetry term in the Weizsacker mass formula, which tries to keep the number of neutrons and protons equal, to an SU(3) Casimir operator (i.e. the Schur's Lemma operator).

Finally, the third and main stage of the project, on which we are currently working, entails exploring much of the space of alternative light quark mass universes by applying our generalized numerical formula. We will also analyze in detail special cases that are especially important.

In our preliminary analysis of sets of light quark mass values in an assumed multiverse, looking for conditions conducive to life—that is, stable clumps of a few charged particles—has provided us with some quite intriguing physics problems as well as some unexpected conclusions.

Exportable Development of the 2.007 Robotics Control System

Shane Colton

Abstract

2.007: Design and Manufacturing I is a sophomore-year mechanical engineering class that introduces students to the fundamentals of engineering design in the context of a robotics contest. The contest control hardware has undergone many iterations over the history of the class, moving to radio control rather than tethered operation in recent years. In this UROP and S.B. thesis project, the contest control system was restructured and repackaged to minimize its dependency on custom hardware in order to make the system more exportable to other schools running similar classes and contests. The control boxes, designed to work with a wide range of batteries and motors for flexible competition hardware, were integrated into a smaller package more conducive to manufacturing should the system be developed into a commercial product. The control hubs for the new system are ordinary desktop or laptop computers outfitted with small USB radio modules and a software set that communicates wirelessly with the control boxes themselves. By utilizing USB radios and widely available video game controllers, the system is no longer dependent on custom joystick or other control hardware and users are given more flexibility of control options. The system is currently running in the spring 2008 version of *2.007*.

1 Introduction

There are many options for low-cost robot control hardware on the market today, such as those available from Innovation First1, Vex2, and Parallax3. Most of these, however, are tied at least in part to a set of proprietary hardware, perhaps a specific battery, motor, or hardware control interface. In setting up an educational robotics competition, especially one like 2.007 in which each individual builds a robot, budgetary constraints require using whatever hardware is available. For example, since every student in the class receives a cordless drill, the drill batteries can be used as the power source for the robot. However, this requires a flexible control system capable of handling a variety of input voltages and motor output options.

Previous work by Dr. Hongshen Ma on the latest version of the control architecture has implemented exactly this flexibility. The controller can handle any input from 12-30 V, measuring the input dynamically and scaling the motor output commands to match the voltage rating of the competition motors. In addition, Dr. Ma pioneered the changeover to more robust digital spread-spectrum radios for the competition in 2005.

The original goal of this UROP project, begun in 2006, was to implement a radio upgrade to compact but powerful ZigBee® radio modules. The radios, developed by Digi (formerly MaxStream) are very new but already widely used in sensing and control networks. During the development, small USB interface boards for the radios were manufactured for convenient radio configuration. However, it was soon discovered that these boards could serve an even more useful purpose: replacing the control hardware required for each driver station with a simple software package running on an ordinary computer. By eliminating the most cumbersome component of the competition hardware and replacing it with a flexible software setup, the system could now be feasibly packaged and exported to other schools looking to run a competition. The development of this new system architecture became an S.B. thesis project to be implemented by the start of the 2008 class.

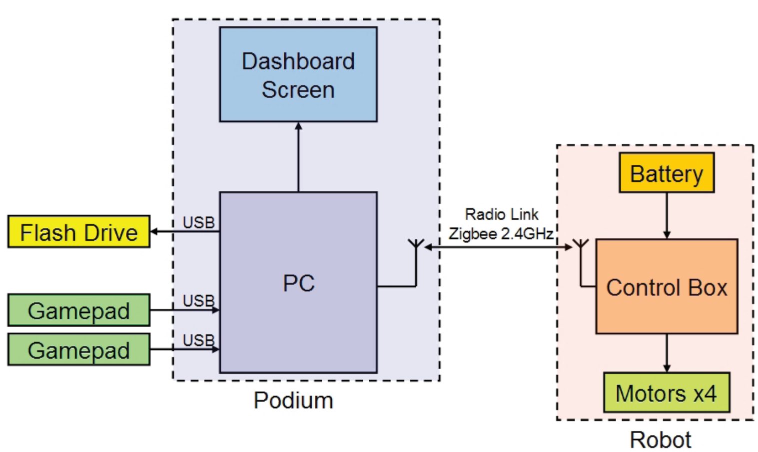

Figure 1: The control system architecture, showing the relationship between the control box and the driver station, referred to here as the "podium."

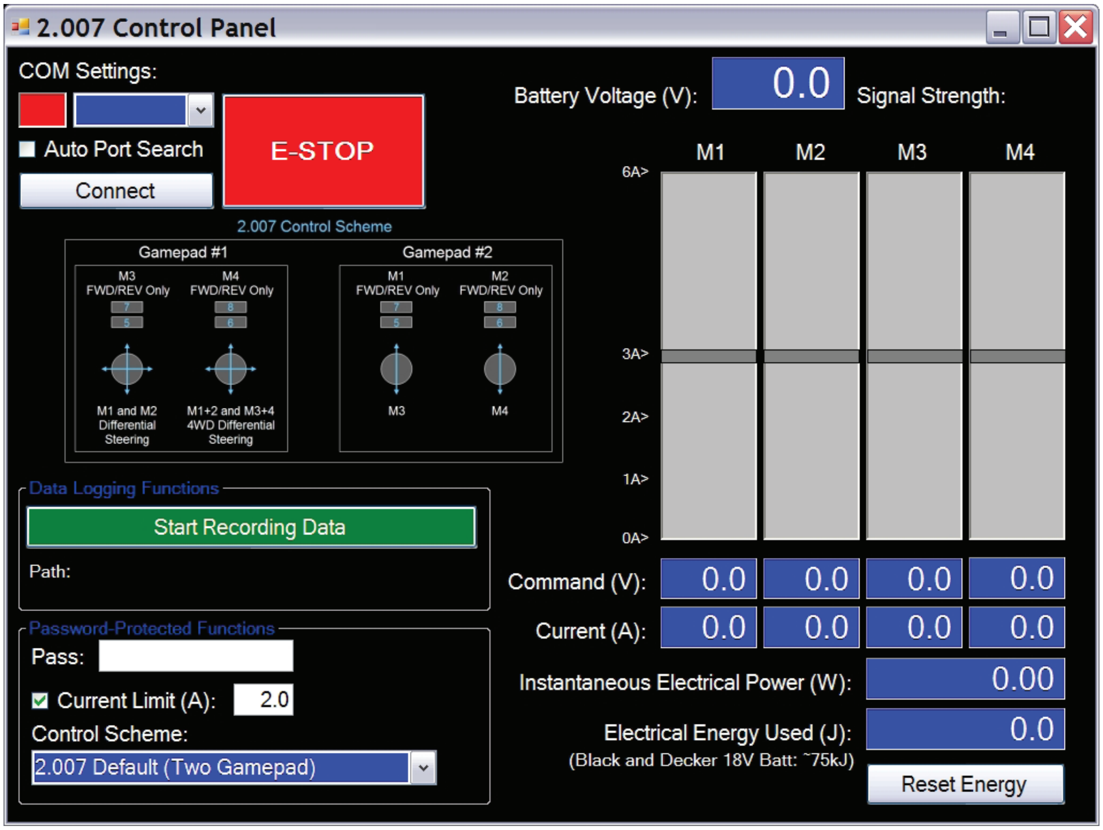

Figure 2: A screenshot of the control interface, displayed on screen at each driver station to provide visual feedback to the robot operator.

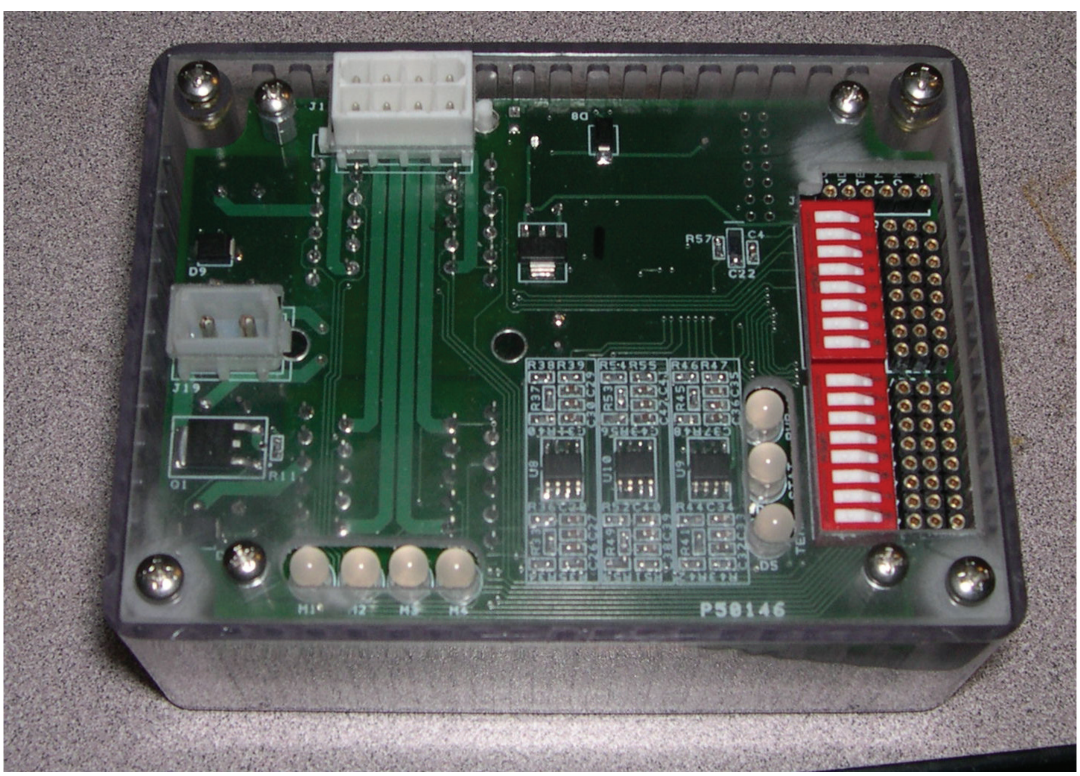

Figure 3: The new 2.007 control box.

2 Methods

2.1 System Architecture

The control system consists of two components: the control box, which resides on the robot itself, and the control hub or driver station, which is off to the side of the competition table in view of the robot. Figure 1 shows the key components of each part of the system and how they interact. The robot operator(s) input commands via one or two USB video game controllers, which could be flight-simulator joysticks, handheld game pads, or any other commonly available USB input device. Software on the control hub computer deciphers these commands and communicates them to the control box via the USB ZigBee® radio modules. The control box, powered in the case of 2.007 by the cordless drill batteries, interprets the commands and generates motor control signals. It also sends back feedback including motor current and battery voltage, which is displayed on-screen at the control hub.

2.2 Radios

The radios utilized are the XBee™ series manufactured by Digi®. They implement a wireless protocol known as ZigBee® in the 2.4 GHz frequency band. Similar to Bluetooth®, ZigBee® is designed for short-range electronic device or sensor networks. Though it has considerably less bandwidth than Wi-Fi®, it consumes less power and is easier to configure. A fully digital, spread-spectrum protocol, ZigBee® radios are less sensitive to interference than low-frequency hobby RC transmitters and receivers. The *2.007* controller operates at a data rate of 9600 bps (bits per second), though the radios are capable of operating at up to 115 kbps, for example in high-sampling-rate sensor networks.

To connect the radios to the control hub computer, USB adaptors were designed and manufactured. To the computer, the radio appears as a virtual serial port, with all the standard serial port options. This makes configuration and software development extremely simple. In the most recent iteration, an on-board microcontroller was added to the radio boards to give them additional functionality as standalone wireless development platforms. Though they are small and simple, the radio boards have been an essential part of this project and will likely be further developed on their own.

2.3 Control Boxes

The control box circuit, still essentially the same design implemented by Dr. Ma, was condensed onto a single printed circuit board with the new ZigBee® radio on-board. In addition to the radio, it has a Texas Instruments MSP430F2274 16-bit microcontroller for executing control commands. Four motor driver ICs channel power from the battery to the motors based on these commands. The motor drivers utilize pulse width modulation, switching transistors on and off at a frequency of approximately 20 kHz to scale the voltage of the battery appropriately based on the commands and programmed motor voltage. The motor drivers have on-board current sensors, and operation amplifiers condition these or other analog signals from external sensors to be read into the microcontroller and reported back to the control hub. The system can also be configured to drive RC servos or a number of higher-power external motor drivers for larger robots.

The circuit board was designed around an off-the-shelf enclosure and all connectors were designed to come through the top of the enclosure to consolidate the custom machining operations onto a single rectangular panel with cutouts. These transparent polycarbonate panels can be cut out by a water jet or laser cutter, or could be molded for mass manufacturing. To ensure circuit reliability and robustness, provisions for reverse-polarity protection, voltage spikes, and heat dissipation from the motor drivers were also included in the design.

2.4 Software Design and Control Interface

The software for the controller consists of two parts: a program written in C and loaded on the microcontroller in the control box, and a program that could be written in any language to handle the control hub operations. The control box software is relatively simple. It communicates with the radio via a hardware serial port known as a UART (Universal Asynchronous Receiver/Transmitter) and translates motor commands into the pulse-width-modulated signal to be amplified by the motor drivers. It also reads in sensor values through an ADC (Analog to Digital Converter) and sends these readings back to the control hub.

Data is transferred via fixed-length packets. Generally, each control signal occupies one byte in the packet, allowing for 256 resolvable levels of motor control voltage. Signals returning from the on-board sensors, however, are 10-bit (1,024 resolvable levels) and so split into multiple bytes. Data integrity is ensured using a technique known as a cyclic redundancy check to deduce whether packets received are complete and uncorrupted.

At the control hub, software written in Visual Basic 2008 maps commands from the control inputs to control values to be sent. A DirectX® library is used to interface to USB input devices and a set of mapping instructions, easily editable in an external file, is used to translate different buttons and joystick axes to motor command values. Data passing is not loop-based: the control hub software will transmit a control packet ever 20 ms regardless of what it receives back. However, 20 ms is generally long enough for the control box to process the data, read sensors, and send a return packet before the next control packet goes out. This allows for the execution of a virtual 50 Hz control loop, though anything requiring faster response time could be hard-coded into the control-box microcontroller itself, which can handle real-time feedback control.

The graphic control interface, displayed on-screen at the driver station, is designed to provide feedback to the driver useful for testing robots and diagnosing problems. Figure 2 shows a screenshot of the control interface, which displays

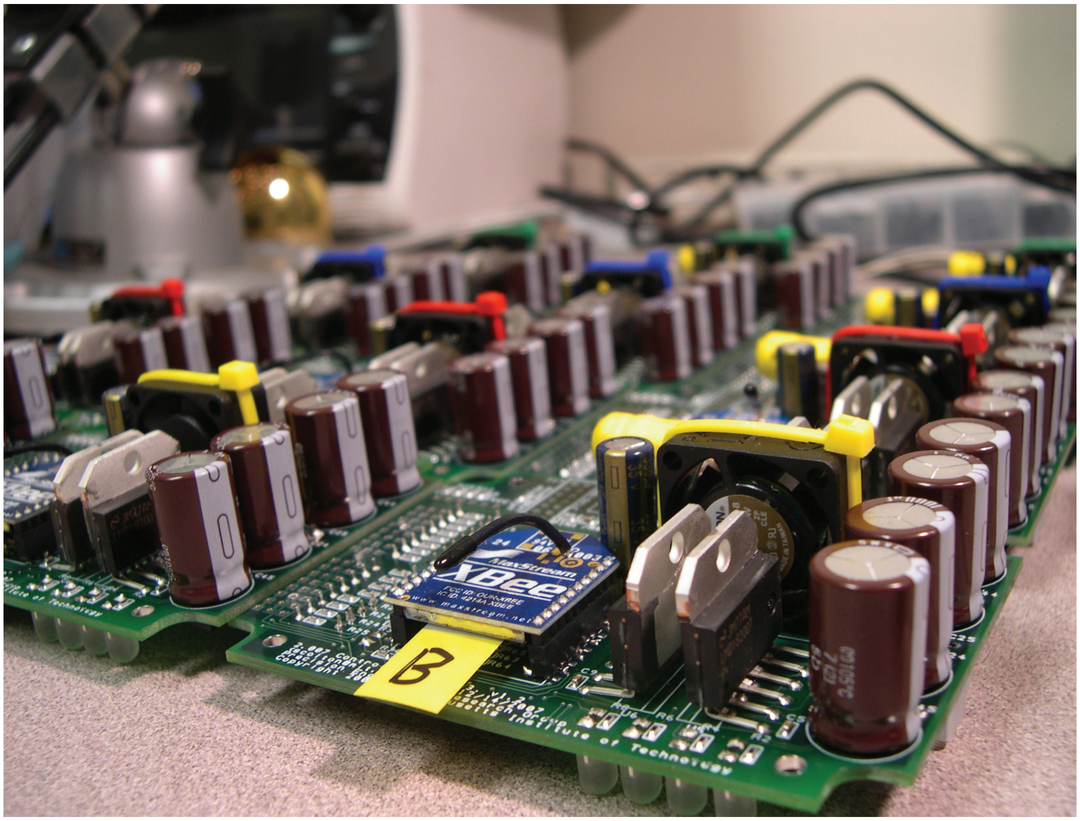

Figure 4: Inside the control box.

motor voltage and currents, battery voltage, power consumption, and other useful data. It is also capable of recording time-stamped data to a file for subsequent analysis.

3 Results and Further Work

Twenty-five of the new control boxes have been manufactured and twelve are currently in use in the spring 2008 version of *2.007*[4]. Figure 3 shows one of the new control boxes. The existing control podiums were retrofitted with desktop computers to run the new control software and interface to the USB radio modules. Both the control boxes and the radio modules have been successfully tested on a number of projects, providing a reliable radio network for wireless sensing and control. The control system may be further tested by a similar class at the University of São Paulo in Brazil, and during the summer as part of the MITES (Minority Introduction to Engineering and Science) program at MIT.

A feature added to the most recent software set allows the control box microcontroller to be programmed wirelessly over the same radio network using the USB radio modules. Microcontroller programming is not required in *2.007*, a mechanical engineering class. However, the ability to program it easily without disassembling the control box opens up new possibilities for teaching embedded control with the same set of hardware, and should increase the commercial appeal of the system.

The radio modules and control boxes, separately and as a complete system, will continue to be developed and tested. The goal now is to begin distributing the system to other users at MIT and elsewhere that can test it and provide feedback useful in developing it as a product. To see the system in action, visit the *2.007* lab (Pappalardo Laboratory, in the basement of building 3) or the final competition on May 7-8, 2008.

Acknowledgements

The author would like to acknowledge the support and design guidance of Professor Alexander Slocum, advisor to both the UROP and thesis component of this project. Additionally, this project was initially far outside the field of study of the author and would not have been possible without the electronics mentoring and know-how of Dr. Hongshen Ma. Thank you also to the many developers who have worked on the 2.007 control system in the past, keeping it up-to-date and well documented, and to the sponsors of the class who make all of it possible.

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Polythiophene-based Organic Field-Effect Transistors

Ranbel Sun

Introduction

Technologies using organic semiconductors have attracted significant research interest in recent decades, due to their potential as low-cost, structurally flexible alternative to traditional technologies using inorganic semiconductors such as silicon (Si). In particular, organic materials are being used as the semiconducting layer in thin film transistors (TFTs). Because of the low processing temperature required to fabricate organic thin films, they are compatible with flexible plastic substrates.[1] The potential to process organic materials from solution also opens up the possibility for large area devices via cost-effective manufacturing methods such as ink-jet printing deposition. Applications can include flexible electronic displays, radio-frequency identification tags (RFIDs), and photosensors.

Currently, the best charge carrier mobilities measured for organic semiconductors (as seen in pentacene) are of the same order of magnitude as amorphous silicon (around 1 cm^2/Vs). However, wet-processed organic semiconductors still exhibit mobilities that are one or more orders of magnitude smaller. In general, lower mobility in organic materials is attributed to the inherently different mechanism of carrier transport and the weak intermolecular bonds in organic compounds.[2] Another important organic field-effect transistor (OFET) limitation is the induction of carrier traps in the organic semiconductor by light and atmospheric conditions which would reduce the mobility and degrade the device. In addressing these limitations, polythiophene semiconductor films have been widely studied due to their high crystallinity and relative air stability under operation. Various polythiophene OFETs have been shown to possess large crystalline domains[3,4] that would facilitate charge carrier transport and lead to higher mobility. Values of up to 0.7 $cm^2/V.s$ have been reported,[3] which are comparable to mobilities for vacuum deposited pentacene.

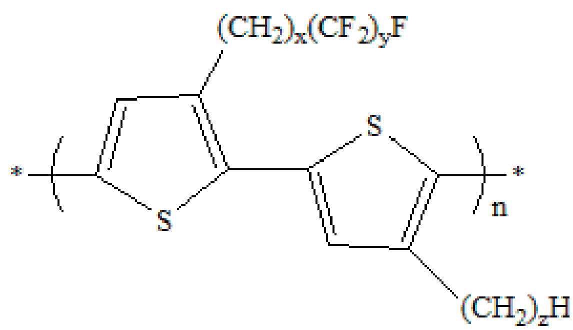

Figure 1: Polythiophene (x,y/z)
Polythiophene (5,4/12), (5,4/8), and (11,4/8) were investigated, differing in the lengths of their alkyl and fluoro substituents.

This research focused on studying newly synthesized polythiophene copolymers (Figure 1) as a potential semiconductor for OFETs. The three different compounds we worked with differed in the lengths of their alkyl and fluorine side chains.

Like in other polythiophenes, the planar π-electron network strengthens intermolecular bonds and results in more rigid crystalline structures. The fluorine chains, however, are particularly interesting because they can potentially segregate and self-align during deposition and further reduce carrier scattering. We hope to fabricate high performance transistors by developing these new materials, optimizing fabrication and processing steps, and investigating self-assembled monolayer (SAM) interfaces.

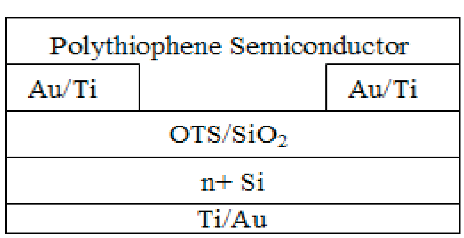

Figure 2: Composition of experimental OFETs in bottom-contact configuration.

Experimental Methods

Device Fabrication:

The OFETs fabricated for this research were in bottom-contact configuration. (Figure 2) A heavily n-doped Si wafer (550 μm) served as both the substrate and the gate electrode, through which voltage could be applied to control the flow of current between the source and drain contacts. The back of the Si was coated with a thin layer of titanium (10 nm) as an adhesion layer for gold (100 nm). Since polythiophene is known to be of p-type (hole-conducting), we used a high workfunction metal for improved hole injection. A 200 nm thick SiO_2 insulator was thermally grown on top of the

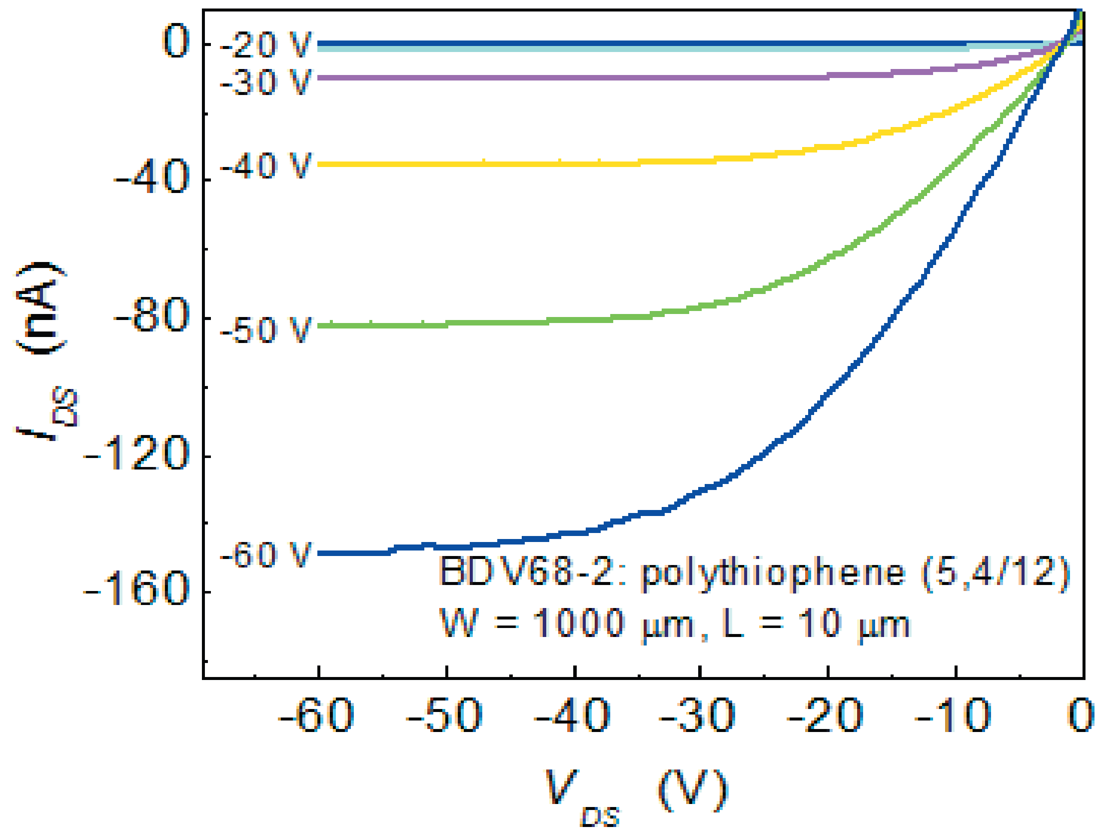

Figure 3: Output characteristics for a polythiophene (5,4/12) transistor with W = 1000 µm and L = 10 µm. The semiconductor is notably p-type, since negative voltage induces charge transport.

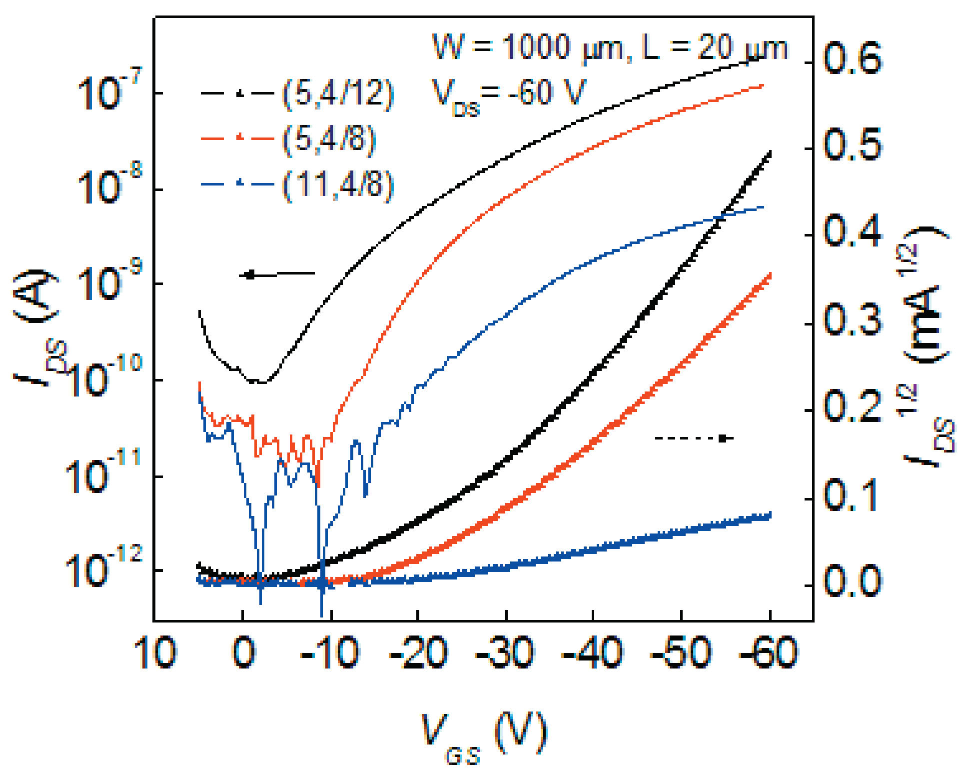

Figure 4: Transfer measurements for polythiophene (5,4/12), (5,4/8), and (11,4/8) devices with W=1000 µm and L=20 µm. The low mobility for the (11,4/8) device is attributed to its thicker semiconducting film.

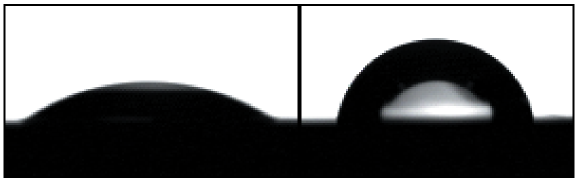

Figure 6: Graphical comparison of contact angle before and after the insulator surface is treated with a PFAPA SAM layer. PFAPA eliminates charge-trapping hydroxyl groups, leading to a more hydrophobic surface.

Si. A thicker insulating layer (or one with a lower dielectric constant) is more effective at reducing gate leakage, but it also inhibits the driving ability of the transistor. Ti/Au (5 nm/100 nm) source and drain contacts were patterned over the dielectric surface using photolithography and a lift-off process. The chips were cleaned extensively in an ultrasonic bath with detergent water, deionized water, acetone, and ethanol. They then underwent 4 minutes of UV-ozone plasma treatment, immediately after which they were submersed overnight in a 0.4 w.t.% octadecyltrichlorosilane(OTS)/toluene solution while in a nitrogen-filled glovebox (<3 ppm H_2O, <12 ppm O_2). OTS formed a self-assembled monolayer by eliminating surface hydroxyl groups which would otherwise trap electrons and inhibit device performance. The prepared chips were baked at 120°C for 30 minutes, cleaned with chloroform and ethanol, and dried on a hotplate.

The polythiophene was solubilized in 1,2-dichlorobenzene at a concentration of 0.25 mg/mL and dropcasted over the contacts in air. Spincoating would have produced a more uniform film, but we chose to dropcast because of the potential to lead to slower film formation and a higher degree of organization.

Phosphonic Acid Treatment:

The phosphonic acid SAM procedure was similar to that for OTS. Substrates were cleaned by sonication and dried on a hotplate. Immediately following a 4-minute plasma etch, the substrate was submersed overnight in a 1mM solution of either alkylphosphonic acid (APA) or perfluoroalkylphosphonic acid (PFAPA) made with a 3:2 ratio of chloroform/ethanol as solvent. The solvent evaporated over time, leaving phosphonic acid molecules adsorbed to the substrate surface. Samples were baked at 140°C for 6-12 hours and underwent post-modification cleaning in ethanol. To verify SAM coverage, contact angle measurements were conducted to test the hydrophobicities of the treated surfaces.

Device Characterization:

In a transistor, applying a certain bias to the gate electrode (V_{GS}) induces the formation of a charge carrier channel through the semiconducting layer, a phenomenon also known as the field effect.[1] A source-drain voltage potential (V_{DS}) results in the movement of these accumulated charges, or in other words an electric current, between the source and drain contacts. Organic semiconductors are usually intrinsically inclined to conduct either electrons or holes and greatly differ in their charge transport ability.

Testing took place in gloveboxes so that H_2O and O_2 would not interfere with device operation. The sample sat on an aluminum block with the gold backing adjacent to the aluminum. Electrical contacts were made to the gate (via the aluminum), source, and drain using a microprobe station and connected to a power source/monitor unit. To generate output curves, we measured the source-drain current (I_{DS}) as a function of V_{DS} for several discrete values of V_{GS}. For transfer measurements, we swept V_{DS} for fixed values of V_{DS}.

The field effect mobility (μ), threshold voltage (V_{TH}), and on/off current ratio (I_{ON}/I_{OFF}) are figures of merit that quantify OFET performance. In the saturation regime, the mobility can be calculated from the square law:

$$I_{DS} \approx \frac{W}{2L} C_i \mu (V_{GS} - V_{TH})^2 \qquad (1)$$

where W and L are the width and length of the semiconducting channel respectively, and C_i is the capacitance density of the SiO_2 insulator. The threshold voltage is the gate voltage necessary to induce mobile charges in this channel, or essentially, when I_{DS} is no longer zero. The on/off current ratio is the maximum over minimum I_{DS} as seen on the transfer curve, another useful characteristic that helps gauge the switching abilities of the device.

Results and Discussion

Polythiophene OFETs:

Figure 3 shows output curves, also known as I-V curves, for a polythiophene (5,4/12) transistor with W = 1000 µm and L =10 µm (W1000L10). We can see that the polythiophene semiconductor is of p-type because current increases with negative V_{DS} and V_{GS}. Typical OFET behavior is observed: The current increases with V_{GS}, and as V_{DS} is swept from 0 V to -60 V, it experiences a linear gain until eventually reaching a saturation value when the conducting channel becomes pinched-off by an insufficient potential between the gate and drain.

Having successfully made devices using this new copolymer, the three polythiophene compounds were compared by taking transfer measurements of transistors with the same channel dimensions. Figure 4 displays a semi-logarithmic plot of the source-drain current (I_{DS}) as a function of gate voltage (V_{GS}) and a plot of $I_{DS}^{1/2}$ for linear fitting purposes.

The polythiophene (5,4/12) gave the highest mobility, 3.3×10^{-4} cm²/V.s., and (5,4/8) performed similarly with a mobility of 2.1×10^{-4} cm²/V.s. However, a significantly lower mobility of 8.7×10^{-6} was measured for the (11,4/8) device. The (11,4/8) was found to have a film thickness of 100 nm, compared to 15 nm for the other two. The disparity in mobility may be attributed to the thickness difference rather than the inherent proper-

Untreated	37°
APA	69°
PFAPA	79°
OTS	89°

Table 2: Contact angles for various SAMs on Si/SiO_2.

t=150 nm	L50	L20	L10	L5
W500	2.9×10^{-5} (-15.3)	4.1×10^{-6} (-33.1)	1.6×10^{-6} (-30.7)	4.3×10^{-7} (-31.9)
W1000	---	1.1×10^{-5} (-20.9)	2.6×10^{-6} (-34.7)	---
t=15 nm				
W500	1.4×10^{-3} (-13.1)	3.3×10^{-4} (-19.0)	1.6×10^{-4} (-21.3)	---
W1000	---	3.7×10^{-4} (-20.5)	3.7×10^{-4} (-27.7)	3.3×10^{-4} (-21.1)

Table 1: Mobility values (cm2/V.s) and threshold voltages (V) for OFETs on two polythiophene (5,4/12) chips with different thicknesses, 15 and 150 nm. Columns correspond to channel lengths and rows to channel widths, as measured in microns.

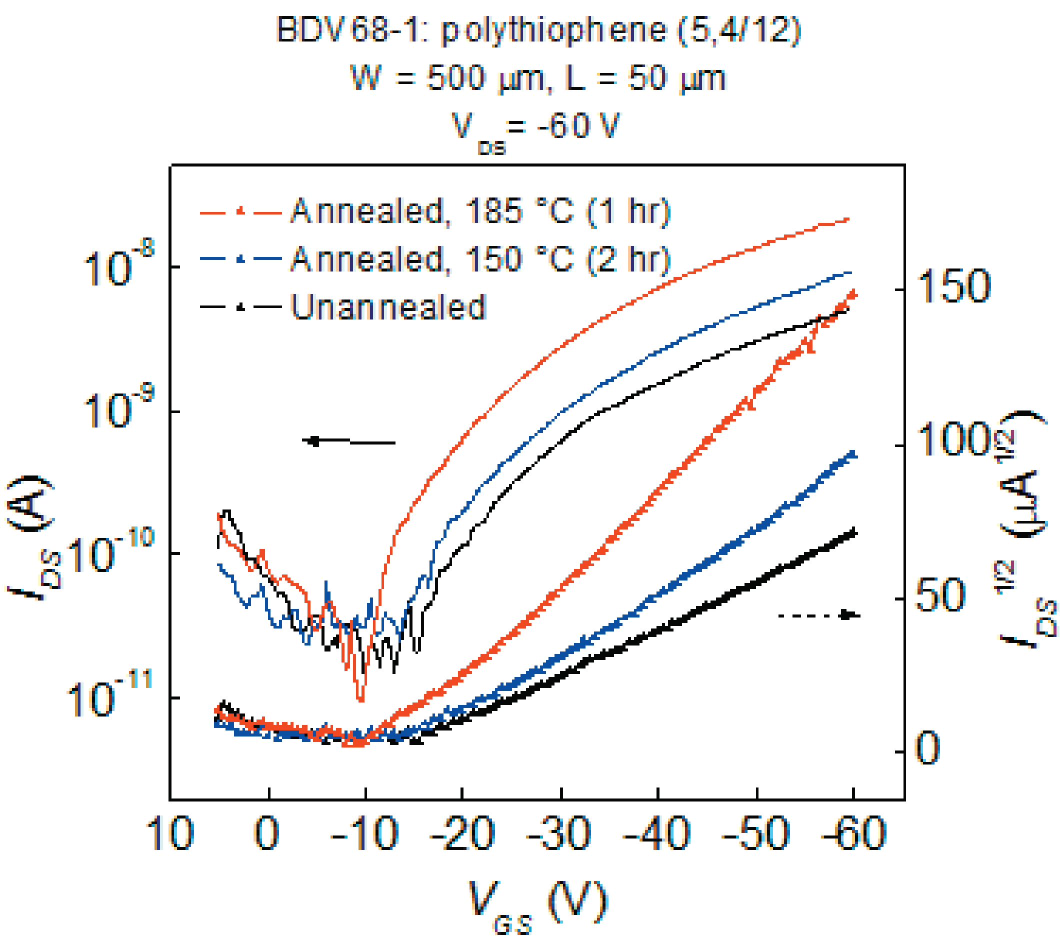

Figure 5: Transfer curves for a 150-nm, W=500 µm and L=50 µm polythiophene (5,4/12) transistor annealed at different temperatures. Annealing produced a noticeable improvement in mobility.

ties of the polymer. This is supported by the data in Table 1, which compared μ and V_{TH} for two (5,4/12) chips with different thicknesses, 15 and 150 nm, for the organic film.

Higher mobilities were achieved with a thinner film, regardless of device geometry. The highest mobility value measured was 1.4×10^{-3} $cm^2/V.s$. Device geometry clearly had an effect on performance, where the best performing transistors had channel widths and lengths of 500 and 50 µm. According to the data, decreasing the length and width corresponded to decreased mobility for this device structure. Ideally, we would like to be able to decrease size without compromising performance. The threshold voltages were also quite high, which is impractical for low-voltage switching applications. I_{ON}/I_{OFF} was on the order of 10^3; it could be increased above its current value if the off-current could be decreased, usually by reducing environmental and measurement noise.

Fabrication/Processing Parameters:

Thermal annealing was performed in order to improve film quality. The energy from heat lets the molecular groups move about more freely and in theory, allows the polymer side-chains to align more uniformly. The 150-nm thick (5,4/12) chip was first annealed to 150°C for 2 hours. After testing, it was annealed again, this time to 185°C for an hour. As shown in Figure 5, annealing produced noticeable improvement in mobility, with values increasing from 2.0×10^{-5} to 1.2×10^{-4} $cm^2/V.s$. Annealing the 15-nm chip to 185°C, however, caused a drop in performance. It is likely that the thinner film had different thermal properties, causing it to melt at lower temperatures than the thicker film.

In addition to controlling film thickness during fabrication, ensuring film continuity is fundamental to obtaining high quality electrical characteristics. A continuous film produced characteristic OFET output curves, whereas the current for a discontinuous film did not saturate. Also, after fabricating several devices, the polythiophene solution was found to degrade when kept in air. Freshly prepared solutions led to better performing OFETs than solutions stored in air for several days. For example, a W=1000 µm L=20 µm device made with a fresh (5,4/8) solution was found to have a mobility of $\mu = 2.1\times10^{-4}$ $cm^2/V.s$ and a threshold voltage V_{TH}= -23 V. After 12 days, a device made with the same solution resulted in a mobility and threshold voltage of 1.2×10^{-5} $cm^2/V.s$ and -44 V. After 27 days, no transistor behavior could be observed.

Fluorinated SAMs:

Table 2 lists the contact angles measured for various SAM layers on Si/SiO_2 substrates. The fluorinated phosphonic acid (PFAPA) was confirmed as a more hydrophobic surface modifier than APA. PFAPA may be a good candidate for fabricating polythiophene OFETs because not only does it have a contact angle comparable to OTS, its fluorine molecules may assist with fluorine chain alignment in the semiconductor.

Conclusion

OFETs fabricated with these polythiophene derivatives achieved promising mobilities of up to 10^{-3} $cm^2/V.s$. Although the mobilities of these new compounds currently do not rival those of existing, high-quality polythiophenes, we have yet to fully explore the exploitation of their fluorine side-chains. Future work will involve fabricating OFETs with the fluorinated phosphonic acid SAM in hopes of creating a well-structure, ordered film. If liquid crystal formation is observed via x-ray crystallography, aligning the crystals may be another method of increasing mobility. Fabrication and processing procedures will certainly need to be optimized, such as improving deposition techniques, finding ideal annealing temperatures, and ensuring that the film is uniform and at an optimal thickness.

Acknowledgments

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Fluid Flow

A two-dimensional Lattice Boltzmann formalism and its application to turbulent flow problems

Peter A. Iannucci

1. Introduction

One of the most intractable problems in modern mathematics is fluid flow. Fluid behavior accounts for natural phenomena ranging from stellar magnetohydrodynamics to respiration and aerodynamics to climatology. There is therefore great demand for accurate solutions to fluid flow problems, especially as they pertain to aerodynamics – for example, how to design cars to minimize wind resistance, how to design buildings to withstand violent storms, how to design high-speed boats, and how to build stealthy, quiet propeller blades for submarines. This investigation will discuss the branch of statistical physics devoted to meeting this demand, build a flow model according to such a statistical formalism, and evaluate the applicability of the model to a physical flow problem with engineering relevance.

2. Fluid Flow Models

To achieve aerodynamic efficiency, prototype designs are refined in simulations of field conditions. Since mock-up construction is expensive and time consuming, engineers work with scale models. Fluids have the particular property that any two flows with similar geometry will show similitude – that is, they will have precise kinematic (flow pattern) and dynamic (drag/lift force) similarity – whenever they have equal Reynolds numbers

$$\mathrm{Re} \equiv \frac{Lu}{\nu} \qquad (1)$$

where L is the length scale of the flow (the length of any common feature); u is the flow velocity; and ν is the kinematic viscosity of the fluid. Thus, for example, a wind-tunnel test at half real scale should be performed at twice real speed to establish similitude.

Less expensive than wind-tunnel simulation is computer modeling. Perhaps the most widely used mathematical model for fluid flow is expressed by the Navier-Stokes equations (Appendix A briefly explains their form). These equations, first derived by Claude Luis Marie Henry Navier in 1822, describe the time evolution of velocity and density within a fluid as a nonlinear partial differential equation. Nonlinearity unfortunately renders these equations notoriously difficult to solve. Fig. 1 depicts one problem for which an exact solution is known: a slow, steady flow over a sphere or cylinder in an infinitely large fluid. Since exact solutions for flow around industrial designs are not available, engineers seek approximate solutions through numerical methods. While in principle a flow could be modeled at the atomic level, this would be wildly impractical [11]. Computer flow simulations in practice suffer from limitations in accuracy and spatial resolution arising from the speed of the computer, its memory capacity, and the specific approximation employed. Note that the Navier-Stokes equations do not apply to plasma magnetohydrodynamics or dense or rare gas flow, as other mathematical formalisms become necessary in those cases. Only Navier-Stokes flow will be considered in this investigation.

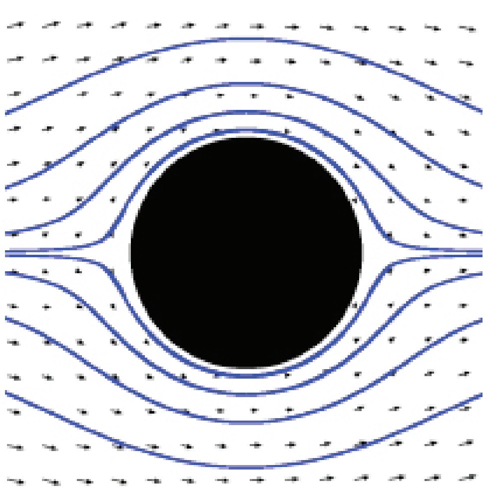

Figure 1: Exact Solution for Steady Flow over a Sphere

In a computer model, the volume of interest is divided into many smaller sub-volumes, and time is divided into short time-steps. Velocity, pressure, density, and temperature must then be computed at each sub-volume for each time-step. In order to resolve small details like waves or eddies in the motion of the fluid, the sub-volumes must be substantially smaller than the smallest flow detail [29]. Generally speaking, the faster the prototype object moves relative to the fluid, the more fine detail will be present in the flow pattern [1]. Making the sub-volumes smaller increases computational cost [5], but failing to resolve this fine detail results in excessive "numerical viscosity" and nonphysical output data. Some heuristic "turbulence" models are available to combat numerical viscosity effects on large sub-volumes, but turbulent phenomena remain poorly understood.

A further issue for many flow algorithms is the restriction that the time-step must be short enough that the fluid never moves more than a fraction of a sub-volume per time-step [17]. In explicit models like the one presented below, the flow variables (velocity, density, etc.) for a sub-volume at one time-step are computed from the flow variables of only the sub-volume and its local neighbors in the previous time-step. Disturbances in distant sub-volumes can propagate through the simulation no faster than the "speed of sound" defined by the lattice spacing and time-step. The actual flow must be substantially slower than the speed of sound in the simulation to avoid inaccuracy or instability. Hence, in order to correctly simulate fast-moving objects like cars, we need small sub-volumes for resolution and short time-steps for stability – both leading to increased computational complexity.

Two major approximations to the flow equations are computational fluid dynamics (CFD) and statistical methods. This investigation concerns the latter. CFD approaches explicitly treat the spatial and temporal derivatives in the Navier-Stokes equations across the flow field and numerically integrate them over time. Statistical methods, on the other hand, are based on the observation that the complexities of fluid flow arise from the interaction of discrete particles. Ludwig Boltzmann developed a set of equations that describe the aggregate statistics of these particle interactions. It has been proven that in the limit, as the scale of the overall flow relative to the individual particle interactions grows large, Boltzmann's equations result in a solution to the Navier-Stokes equations [14]. Another statistical model is the Direct Monte Carlo method, useful for rarified gas flow at high speed.

3. Engineering Problem

The objective of this investigation in statistical physical flow modeling calls for a specific engineering problem involving the turbulent flow phenomena to be examined. A perfect historical example is the November 7, 1940 resonance-driven failure of the Tacoma Narrows Bridge (Fig. 2; see also Appendix B) due to von Kármán vortex shedding.

Von Kármán vortex shedding occurs downstream of a bluff body in a flow. As the fluid first encounters the upstream side of the obstacle, it slows and forms a high-pressure region. The fluid is diverted around the obstacle, and the two streams eventually rejoin and flow away downstream. Directly behind the obstacle, a region of low pressure is formed. If the fluid is moving fast enough, two symmetric counter-rotating eddies form in this low-pressure region (Fig. 3). If the fluid moves faster still, the eddies stretch downstream, up to several times the diameter of the original obstacle (Fig. 4). Eventually, if the Reynolds number of the flow exceeds a critical value near 60, this configuration becomes unstable and symmetry is spontaneously broken through the interaction of the two eddies. One eddy detaches and is carried downstream from the obstacle, and a new eddy forms in its place (Fig. 5). Next, the other eddy detaches and reforms, and so on. Such

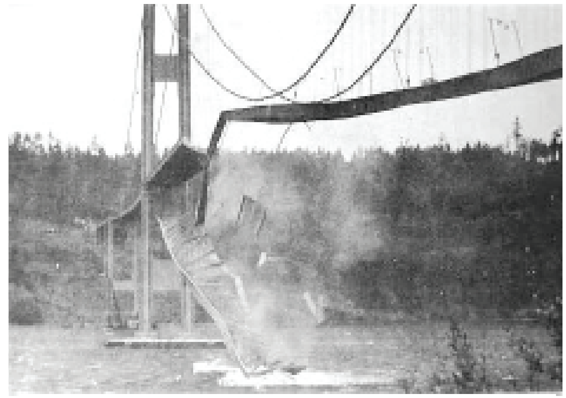

Figure 2: Structural Failure of the Roadbed of the Tacoma Narrows Bridge [15]

eddies are referred to as vortices, and their periodic detachment is *vortex shedding*. If unimpeded, the vortices are carried downstream in a "vortex street" for a great distance before they disappear. Vortex shedding places a time-varying transverse load on any structure exposed to external flow. This includes strung wires, bridges, tall buildings, and even islands. Shedding causes wires to whistle in the wind, and is responsible for beautiful cloud formations visible to the lee of islands under favorable conditions (Fig. 6). More concerning, shedding around a skyscraper can cause structural damage, and shedding behind an airplane wing can lead to a stall or crash. Clearly, vortex shedding well merits detailed study. Among unsteady flow patterns, it is also one of the simplest to model, making its accurate simulation an important benchmark for the calibration of a numerical flow code. For this investigation, a numerical simulator capable of reproducing vortex shedding will be described and built. Such a simulator will demonstrate the complexity and beauty of fluid flow pro lems in general, while remaining modest in its computational requirements – a necessity as it will run on a single 3.0 GHz computer with 1024 MB of memory, and will be allowed no more than a few days per simulation. Figs. 3-5 give a preview of the simulator's output. The simulated shedding frequency will be compared with reference estimates of the true, physical shedding frequency at the same Reynolds number, and error figures will be computed for the simulator's output.

4. Lattice Boltzman Model

With an engineering problem in mind and a goal and benchmark in hand, we must now construct the statistical flow model which will be used for the simulator. As Boltzmann observed, the motion of individual fluid particles is characterized by two behaviors: first, free motion along their direction of travel; and second, interactions with other particles. In general, the latter includes two- and multi-body collisions, non-linearities arising from molecular alignment, and potentials related to alignment and separation which give rise to freezing, boiling, and condensation effects. For many cases of interest, particularly subsonic dry gas flow at atmospheric pressures, multi-body collisions are negligible and alignment and separation effects can safely be ignored. In accordance with the Second Law of Thermodynamics, the remaining interactions must tend over time to maximize local entropy throughout the flow, eventually reaching local thermodynamic equilibrium.

Boltzmann's transport equation describes the probability of finding a particle at some location moving in a certain direction. It can be seen that if all particles move without interacting, their positions vary linearly with time. Hence, the likelihood of finding a particle at time t and location $\bar{x}$ is equal to the likelihood of finding it at some later time $t + \Delta t$ and location $\bar{x} + \bar{u} \cdot \Delta t$, where $\bar{u}$ is the particle velocity: it has simply moved in a straight line. Therefore,

$$f(\bar{x} + \bar{u} \cdot \Delta t, t + \Delta t, \bar{u}) = f(\bar{x}, t, \bar{u})$$

$$f(\bar{x} + \bar{u} \cdot \Delta t, t + \Delta t, \bar{u}) - f(\bar{x}, t, \bar{u}) = 0 \quad (2)$$

Here, $f(\bar{x}, t, \bar{u})$ is the distribution of particles with velocity $\bar{u}$ at position $\bar{x}$ and time t, and the time-step is Δt. If the particles interact during this time, we can add a correction term such that the difference between the distributions at time t and $t + \Delta t$ is equal to a "collision operator" Ω:

$$f(\bar{x} + \bar{u} \cdot \Delta t, t + \Delta t, \bar{u}) - f(\bar{x}, t, \bar{u}) = \Omega \quad (3)$$

Since the collision operator should cause the flow to tend towards local thermodynamic equilibrium, we specify the collision operator as a relaxed approach to local equilibrium at a rate inversely proportional to some time constant τ. This is known as the Bhatnagher-Gross-Krook (BGK) method, and it is expressed as

$$f(\bar{x} + \bar{u} \cdot \Delta t, t + \Delta t, \bar{u}) - f(\bar{x}, t, \bar{u}) = -\frac{1}{\tau}\left(f(\bar{x}, t, \bar{u}) - f^{eq}(\bar{x}, t, \bar{u})\right) \quad (4)$$

The function f^{eq} on the right is the local thermodynamic equilibrium distribution. The rate of approach to this equilibrium, governed by τ, determines the average distance over which particles move before undergoing a collision. This distance, the mean free path, determines the kinematic viscosity of the flow and hence, for a given flow geometry and speed, the Reynolds number of the flow. Thus, the BGK method allows the experimenter to specify the Reynolds number of the flow by adjusting the kinematic viscosity, making it straightforward to establish similitude between the simulation and true physical flow conditions.

For simplicity, the BGK equation is generally evaluated in two steps: all particles are first blindly advected without collision along their direction of travel for one time step Δt, and then collisions are performed throughout the computational volume. These steps are known as the "move" and "collide" stages, respectively, and may be executed in sequence many times to compute the fluid state at a later time from that at an earlier time.

The method thus far described is still computationally inconvenient, because particles can exist at any location in continuous space and they can be traveling in any direction. We can simplify the problem of deciding whether particles collide by discretizing space and forcing the particles to exist at

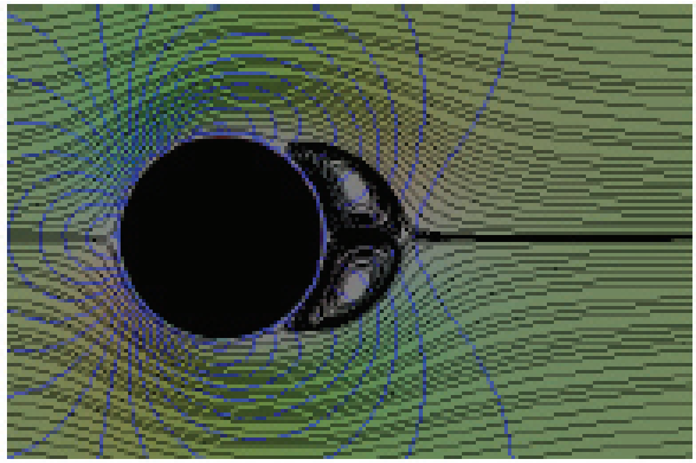

Figure 3: Eddies Forming in the Wake of a Circular Cylinder (these frames from simulator written by investigator)

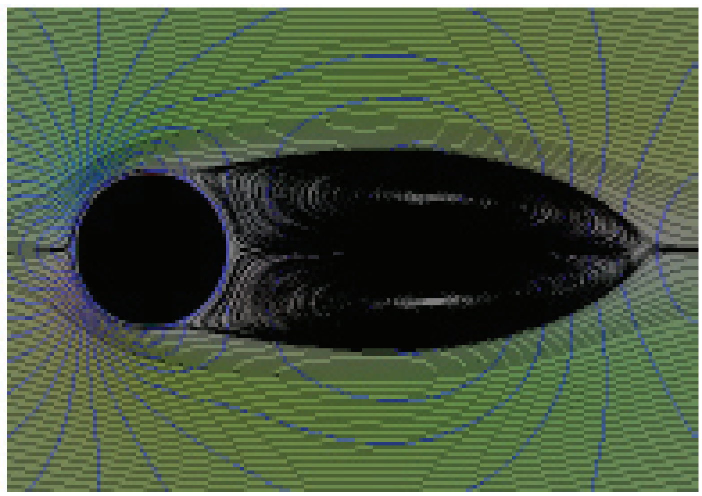

Figure 4: Longer Eddies

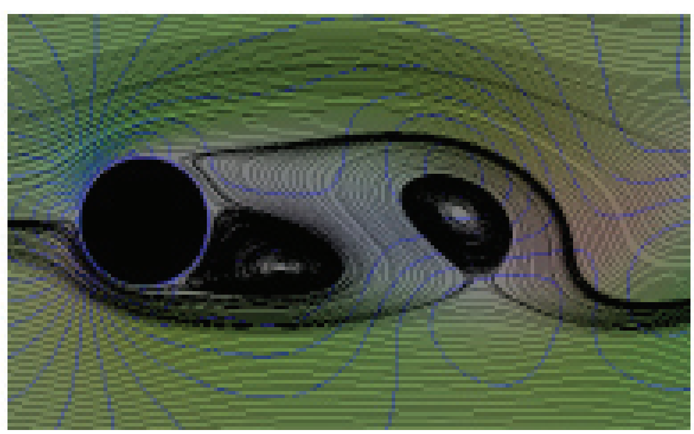

Figure 5: Vortex Shedding

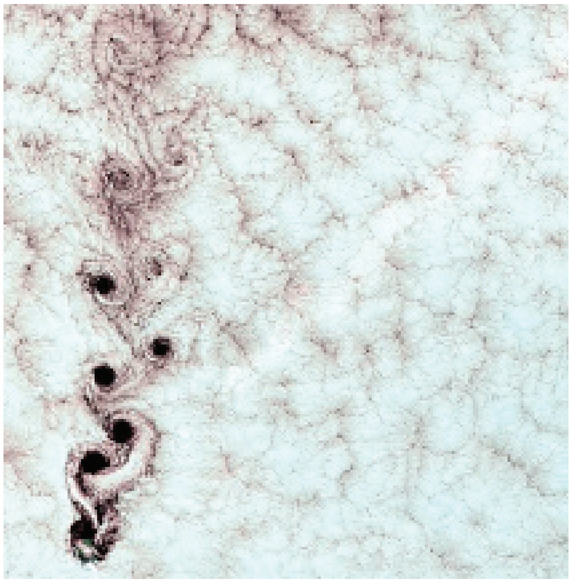

Figure 6: Kármán Vortex Shedding to the Lee of Alexander Selkirk Island [16]

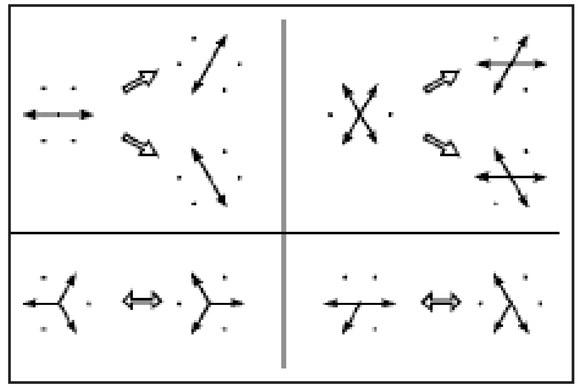

Figure 7: Collision Rules for FHP model [18]

one of a finite number of regularly-spaced nodes on a lattice. Since particles travel between lattice nodes, but cannot travel to locations between nodes, the velocities of the particles must be discrete as well. When two particles are at the same node and traveling in different directions, they collide and rebound randomly subject to conservation of mass, momentum, and energy. Such a system of discrete particles moving along links of a discrete lattice and colliding according to simple rules is known as a Lattice Gas Automaton (LGA). At first glance, it seems ridiculous that a system of particles moving on a regular lattice with discrete velocities could ever approximate continuum fluid flow, since some directions on a lattice are "easier" than others for particles to travel. However, it turns out that with a prudent choice of the lattice and a small but symmetric set of discrete velocity vectors, lattice flow can be made macroscopically isotropic and proper thermodynamic flow statistics can be recovered [22].

Lattice Gas Automata are explicitly conservatory: since particles and velocities are discrete quantities which are carried along the lattice and neither created nor destroyed, the model is guaranteed to conserve mass, momentum, and energy. Early LGA codes, such as the model of Frisch, Hasslacher, and Pomeau (FHP) on a hexagonal grid (Fig. 7), required that only one particle or no more than some small finite number of particles exist in any given node traveling in any given direction at a time. Such a restriction is analogous to the Pauli Exclusion Principle for fermions, and for low maximum particle counts it results in a flow which obeys Fermi-Dirac statistics. However, for correct macroscopic behavior, it is desirable that the flow should instead obey Maxwell-Boltzmann statistics, and hence it follows that a large number of particles should be allowed per node. The greater the number of particles, the more accurate and less statistically noisy the flow approximation. In the limit as the number of particles goes to infinity and the particle mass goes to zero (so that density remains constant), the integer particle counts of the Lattice Gas method are replaced by real number particle densities, or distributions. The result is the Lattice Boltzmann, or LB method. Some significant differences between the LGA and Lattice Boltzmann formulations are given in Appendix C. Combined with the BGK formulation described above, the LBGK method is commonly expressed by the following equation:

$$f_i(\vec{x}+\vec{c}_i\cdot\Delta t, t+\Delta t) - f_i(\vec{x},t) = \Omega_i$$
$$= -\frac{1}{\tau}\left(f_i(\vec{x},t) - f_i^{eq}(\vec{x},t)\right) \qquad (5)$$

Here, $f_i(\vec{x},t)$ is the particle distribution along discrete velocity direction i at position $\vec{x}$ and time t. The velocity vector for direction i is written as $\vec{c}_i$, the time-step as Δt, and the collision operator for direction i as Ω_i. The function f_i^{eq} on the second line is the local thermodynamic equilibrium distribution for direction i. Lastly, as mentioned above, τ is a relaxation coefficient related to the kinematic viscosity of the simulated fluid. Detailed analysis beyond the scope of this investigation shows in particular that

$$\nu = \frac{2\tau - 1}{6} \qquad (6)$$

Since kinematic viscosity must be nonnegative, $\tau \geq \frac{1}{2}$.

To fully specify the flow model for the simulator, it remains to choose a lattice and to determine the expression for the equilibrium distribution and the behavior of the boundaries. The choice of lattice is dependant on an isotropy condition and the dimensionality of the flow under investigation, while the equilibrium distribution is determined by the Maxwell-Boltzmann distribution function and the boundaries are specific to the problem under investigation. Although three-dimensional flow models are of great importance for both theoretical and practical applications, the focus of this investigation will be limited to two-dimensional flow due to the computationally demanding nature of three-dimensional flow and the essentially two-dimensional nature of von Kármán vortex shedding at low Reynolds numbers. A justification of this limitation and detailed discussion of the two-dimensional simulation lattice can be found in Appendix D.

In general, the equilibrium distribution for a lattice is a function of the total mass, momentum, and thermal and kinetic energy at a given lattice node. We will limit ourselves to isothermal flow for simplicity: it can be assumed that the temperature of the flow is everywhere uniform and non-zero, and hence that thermal energy is constant and the equilibrium distribution is a function only of mass and velocity (since p = mv and KE = $\frac{p^2}{2m}$). This assumption is justified for low Reynolds number vortex shedding in subsonic dry gas flow since the true physical phenomenon does not show significant temperature gradients.

As a first step to deriving the equilibrium distribution, it is assumed that all velocities in the simulation are small relative to the grid spacing and time step and hence that the equilibrium distribution can be considered equal to a stationary equilibrium plus a small perturbation dependant on the fluid velocity. Then the equilibrium can be approximated by a Taylor polynomial for the Maxwell-Boltzmann distribution accurate to some order – generally second order or better. This process is elucidated somewhat by [7], which also gives the final coefficients for the resulting polynomial. See Appendix E for the full equilibrium expression and an explanation of its parts.

The boundary conditions for the simulation were designed following a recommendation by Dr. Hudong Chen, an expert in the field. Essentially, obstacles cause impinging flow to be reflected back along its path, and cells fractionally filled by obstacles reflect a corresponding fraction of incoming flow. The full specification of the boundary treatment is given in Appendix F.

5. Simulator

The simulator was written in C++ using the Microsoft Visual C++ compiler, with development beginning in early 2006 and continuing to the present day. Its basic architecture has evolved substantially since the investigator wrote the first version, but the most recent design follows. Each run of the simulator begins with a problem definition, input as an XML configuration file (a description and example of which may be found in Appendix F) and encapsulated by an instance of the class *Problem*. This definition includes all necessary parameters and boundary conditions for the simulation. Once the dimensions of the simulation grid are known, memory is allocated for two instances of the *Lattice* class. The reader may recall the division of the Lattice Boltzmann calculation into a repeated sequence of "move" and "collide" steps mentioned above. While all "collide" operations can be performed in-place on a single *Lattice* object in memory, "move" operations require separate input and output *Lattices*, which are swapped after each "move". During the "move", particle distributions for each sub-volume are shifted one step along their directions of travel. This is carried out according to equation (F.1) (see Appendix F) by the following statement from Lattice.cpp (altered for legibility; variable names have been changed to match equation F.1):

```
out[j].N[i] = (1 - in[j].Ps) * in[j - move[i]].N[i] +
              in[j - move[i]].Ps * in[j ].N[reverse[i]];
```

Here, *out[ ]* is the output lattice, *in[ ]* is the input lattice, $i \in \{0...8\}$ indicates one of the nine lattice directions (Fig. F.1; see Appendix F), and *j* is the index of the current sub-volume, equal to row * (grid width) + column. *move[i]* contains the offset to the nearest neighbor for direction *i*, and *reverse[i]* indicates which of the nine lattice directions travels in the opposite direction from *i*. A "move" is performed by executing this statement for each lattice direction and each sub-volume over the entire grid.

The "collide" operation is executed according to equation (E.1) (see Appendix E) by the following statements from Lattice.cpp, again altered for legibility. The flow density, horizontal velocity, and vertical velocity for a sub-volume have already been computed as *rho*, *ux*, and *uy*, respectively.

```
// relax towards the equilibrium distribution and store the result in out[]
for(i = states-1; i >= 0; i--) {
      // compute equilibrium according to equation (B.1)
      uDotC = ux*ckix[i]+uy*ckiy[i];
      v = Wk[i] * rho * (1 + 3*uDotC + 4.5*uDotC*uDotC - 1.5*(ux*ux+uy*uy));

      // use LBGK relaxation to compute output distribution
      v = lattice[j].N[i] - oneovertau * (lattice[j].p[i] - v);

      if (v < 0) {                    // limit density to positive numbers,
            negativeDensity -= v;     // but record negatives as errors
            v = 0;
      }
      lattice[j].N[i] = v;            // store output distribution
}
```

Looping over the velocity states of the lattice, this code evaluates the polynomial from (E.1), substitutes the result into the LBGK equation, and stores the resulting final distribution in *lattice[ ]*. A "collide" is completed once this code has been executed for each sub-volume in the simulation.

Each "move" and "collide" pair represents one timestep in the evolution of the simulated fluid. Periodically, the simulator examines the flow state and generates a visualization of the flow. This can be done in several ways- so far, the investigator has implemented support for streamlining, pressure contours, line-integral-convolution streaklining, rendering vorticity (rotation) to shades of gray, and a hue-saturation-value system to depict the direction, strength, and density of the flow, respectively. The simulator can also produce audio output by sampling fluid pressure over time at a predetermined "microphone" location. These tools are useful for monitoring the state of the simulation and, when recorded to disk in sequence, the visualizations allow an animation of the flow to be produced. Moreover, the sequence of images generated for flow past a cylinder allows the investigator to measure the precise frequency of vortex shedding.

6. Experimental Reference and Problem Specification

The experimental reference for this investigation will be taken from [122]. An empirical formula from that source relating Strouhal number to Reynolds number allows the investigator to estimate the frequency of vortex shedding to be expected from a given simulation. Strouhal number is defined as

$$\mathrm{St} = \frac{f \cdot L}{u} \qquad (7)$$

where f is the frequency of oscillation of the flow, L is the length scale – in this case, the cylinder diameter – and u is the flow speed. The empirical relation between Reynolds number and Strouhal number for laminar flow past a cylinder is given by

$$\mathrm{St} \approx \frac{A}{\mathrm{Re}} + B + C \cdot \mathrm{Re} \qquad (8)$$

where $A = -3.3265$,

$B = 0.1816$, and

$C = 0.00016$

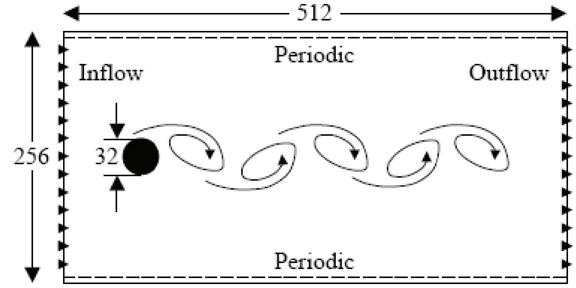

Figure 8: Simulator Setup: Unsteady Laminar Flow Past a Cylinder, Showing Dimensions in Grid Units

The simulator is set up as shown in Fig. 8. The free stream velocity is set to 0.05, about 9% of the speed of sound, and the viscosity is adjusted by setting τ such that Re=150. This value for the Reynolds number is well above the critical value for the onset of shedding (about 60) and well below the Reynolds number at which vortex shedding ceases to be primarily two-dimensional (about 270). The XML problem description used for this configuration is given in Appendix G.

7. Results

After some 50,000 time steps, the simulator visualization begins to look like Fig. 9, with a beautiful Kármán vortex street appearing downstream from the cylinder. The variable visualized here is vorticity, with clockwise rotation in white and counter-clockwise rotation in black. Gray areas indicate vorticity values near zero.

The simulation was terminated after roughly 80,000 times steps, and frames from the sequence of output images were visually compared to determine the period of oscillation of the flow. A frame was chosen in which the flow had clearly reached steady state: at time step 51,856. Frames before and after it were selected such that in each the final counter-clockwise (black) vortex was just about to disappear off the right-hand side of the simulation. The frames found to meet this criterion are indicated in Table 1.

From the period data in the second column of Table 1, we can conclude that after the initial transient the period stayed roughly constant at an average of 3046 time steps. This corresponds to a frequency of $3.283 \cdot 10^{-4}$ cycles per time step. From relation (8), we find St$\approx$ 0.18342, which by (7) gives a reference "true" frequency of $2.866 \cdot 10^{-4}$ cycles per time step. The relative error of the simulation result, therefore, is about 15%.

8. Conclusion and Suggestions for Further Work

While the size of the error in the simulation result is somewhat disappointing, a number of possible resolutions are available. First, the channel around the obstacle could be made wider by a factor of two or more to reduce pressure influence from "neighboring" cylinders through the periodic boundaries. Second, the resolution of the obstacle could be increased. This could be accomplished by increasing the resolution of the entire grid, or a more sophisticated local grid refinement algorithm could be employed. Third, as simulation accuracy improves and the "eye-ball metric" becomes less favorable for computing the oscillation period, a calculation of the time-varying drag force on the cylinder could be carried out by summing the momentum transfers from each boundary interaction along its surface. The oscillating transverse component of the drag could be fit to a sine curve to give a good estimate of the oscillation period of the vortex street. There is clearly room for a great deal of additional study in understanding the factors contributing to the accuracy or error of this simulation.

As an introduction to fluid flow phenomena and their numerical simulation, however, this exercise has proven most fruitful. It has given the investigator an opportunity to study flow models and approximations, lattice isotropy and tensor mathematics, and experimental work and practical applications of flow engineering. In retrospect, the investigator feels that one of the most severe limitations encountered in this investigation was neither mathematical nor academic, but rather computational: with the limited random access memory and limited processor speed of a household computer, feasible simulations were limited in size and accuracy. The local grid refinement algorithm proposed would save memory and improve resolution, as would a host of other optimizations. The investigator only regrets being unable to implement such advancements in the limited time and space of this investigation. Flow problems are crucial to many areas of engineering, and the investigator is not unpleased with the results achieved herein and the entry made into this fascinating subject.

Table 1: Oscillation Data from Simulation

Time Step	Period (Δt)
35120	–
42240	7120
45600	3360
48848	3248
51856	3008
54864	3008
57984	3120
61024	3040
64064	3040
67136	3072
70160	3024
73216	3056

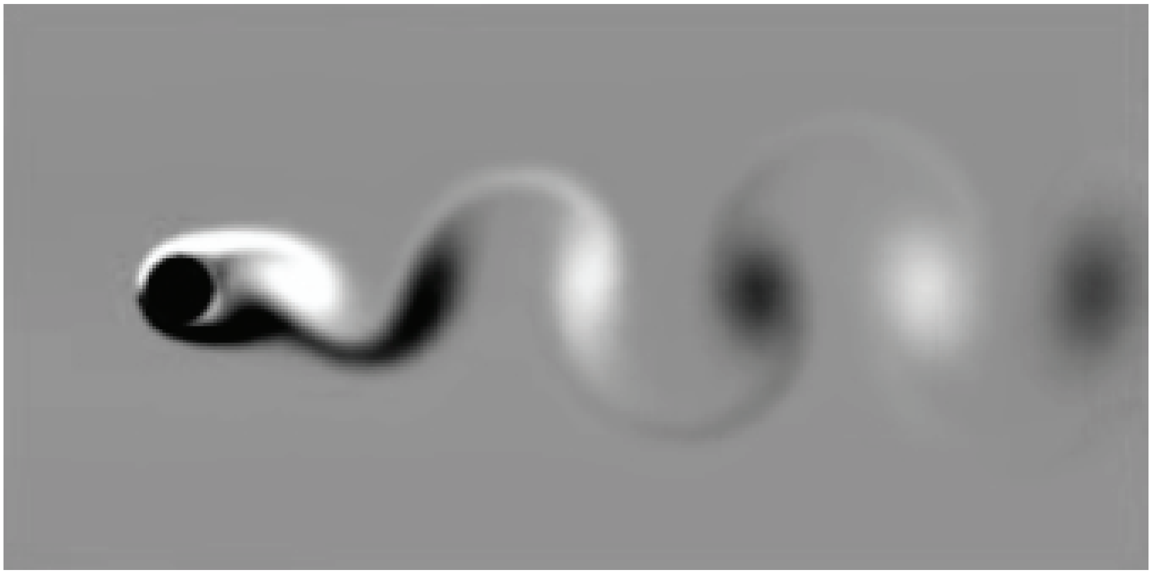

Figure 9: Simulator Vorticity Visualization Showing Well-Developed Vortex Street After About 50,000 Time Steps

Acknowledgements

The investigator would like to thank Dr. Hudong Chen for valuable conversations and the suggestion of the boundary formulation for the simulator. Thanks are also due to Dr. Robert Iannucci, the investigator's father, for illuminating discussions, for his proposal of the grid-filling streamline spacing algorithm used to generate Figures 3-5, and for the referral to the work of Chris Teixeira in FCHC lattices.

Appendices

This paper has been abbreviated due to space limitations. The full version, including references, is available online at:

http://peter.rail.com/lbpai062.pdf