GROWTH IN RESEARCH

<table>
<thead>
<tr>
<th>Year</th>
<th>Research Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>$25.8 million</td>
</tr>
<tr>
<td>2003</td>
<td>$48 million</td>
</tr>
<tr>
<td>2004</td>
<td>$49.3 million</td>
</tr>
<tr>
<td>2005</td>
<td>$55.4 million</td>
</tr>
<tr>
<td>2006</td>
<td>$59.7 million</td>
</tr>
<tr>
<td>2007</td>
<td>$63.6 million</td>
</tr>
<tr>
<td>2008</td>
<td>$67.8 million</td>
</tr>
<tr>
<td>2009</td>
<td>$69.9 million</td>
</tr>
<tr>
<td>2010</td>
<td>$84 million</td>
</tr>
<tr>
<td>2011</td>
<td>$90.1 million</td>
</tr>
</tbody>
</table>

YEAR | FACULTY |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1999/00</td>
<td>89</td>
</tr>
<tr>
<td>2000/01</td>
<td>95</td>
</tr>
<tr>
<td>2001/02</td>
<td>94</td>
</tr>
<tr>
<td>2002/03</td>
<td>100</td>
</tr>
<tr>
<td>2003/04</td>
<td>105</td>
</tr>
<tr>
<td>2004/05</td>
<td>111</td>
</tr>
<tr>
<td>2005/06</td>
<td>115</td>
</tr>
<tr>
<td>2006/07</td>
<td>117</td>
</tr>
<tr>
<td>2007/08</td>
<td>116</td>
</tr>
<tr>
<td>2008/09</td>
<td>118</td>
</tr>
<tr>
<td>2009/10</td>
<td>113</td>
</tr>
<tr>
<td>2010/11</td>
<td>125</td>
</tr>
</tbody>
</table>

PRATT PRIDE

2 Rhodes Scholars
3 Marshall Scholars
6 Goldwater Scholars
7 Fulbright Scholars
2 Churchill Scholars

Pioneers of 3D Ultrasound techniques used around the world in every medical specialty

First accredited biomedical engineering program in the U.S.

Inventors of landmine and explosive device detection techniques used by the military

First to explain the mechanics of DNA spiral shape
MESSAGE FROM THE DEAN

THIS IS NOT YOUR USUAL RESEARCH PUBLICATION. You will not find a comprehensive overview of the many wonderful programs of research in the Pratt School of Engineering at Duke University or even a sampling by department. Instead I asked science writer Dennis Meredith to tell the story of Duke Engineering by focusing on a few areas where Duke is not just a contributor but the leader in defining and opening new fields that tie to grand challenges for engineering and society. The result is a publication in two parts. The fall issue profiles the four areas of Engineering Physics including metamaterials, computational optics and quantum computing, Aeroelasticity, Biomaterials, and Environmental Nanotechnology/Chemistry. The spring issue will feature Data Analytics, Bio-photonics and the computational Materials Genome project.

This publication is atypical in other ways as well. In order to tell the story in each area, Dennis found that he had to interview principal investigators from other schools at Duke and top university partners in the Research Triangle and across the nation. I received amusing emails from faculty in other schools wondering if there was some mistake that they were being asked to interview for a “Pratt” brochure! Not at all.

While Duke Engineering is no longer small—external research funding has been the fastest growing among the top tier in the past decade, rapidly approaching $100 million per year on a base of 120 tenure track faculty—its outrageous ambition has always exceeded what its internal staffing could support. As a result, a culture of collaboration has developed between Pratt and other units that has become part of our secret sauce. For example, medical school faculty play a key role not only in our flagship Department of Biomedical Engineering, but in every department in the Pratt School.

I hope you will enjoy reading the stories about the truly transformative research featured in this issue. I hope you will also enjoy reading about the remarkable people who are making it happen, including brief profiles of several new faculty this year and one special alumnus, Jeff Vinik, whose gift with his wife Penny created 10 new endowed professorships in grand challenge engineering areas.

Sincerely,

Tom Katsouleas
Vinik Dean of the Pratt School of Engineering
“Engaging in leading edge research that involves fundamental discoveries applied to the grand challenges of our time.”

- PRATT RESEARCH MISSION
Building impossible things

Exotic devices from cloaking metamaterials to gigapixel cameras emerge from Pratt engineering physics

Beneath the Atlantic, a nuclear attack submarine cruises the depths, the object of an intense search by its adversary’s sonar. But despite the submarine’s 362-foot length, it remains totally invisible to the enemy’s sophisticated probes. The submarine is swathed in a metamaterial cloak that causes sound waves to slide around its hull with no telltale reflection.

On the surface, a thousand-foot-long tanker slices through the water, fully loaded with crude oil. But incongruously, the behemoth ship leaves a wake no larger than a pleasure boat’s, saving enormous fuel. The tanker’s below-water hull is covered with perforated plates fitted with small water pumps that make it “invisible” to the water through which it plows.

A driver speeds silently along the freeway in his electric car. He notices that his battery charge is low. Fortunately, he sees a sign that says “Charging Lane Ahead.” He swings into the lane, driving for a few miles until his meter indicates a full charge.

An avid football fan sits in his living room cheering for his home team. In a panoramic view of the field, he watches a touchdown play unfold on his TV screen. But the referees question whether the pass receiver was in bounds, so the fan touches a button and zooms in until he can see the receiver’s toes dig into the turf an inch inside the line. Score!

While these products are still only dreams, Pratt’s engineering physicists have already created the underlying enabling technologies. What’s more, the researchers expect those technologies to yield many more such “impossible” machines.
Perhaps the most startling new devices under development at Pratt are those made of metamaterials. These artificially structured materials have no analog in nature. Their precisely engineered structure is designed to exhibit properties that only a decade ago would have been considered pure science fiction.

For example, straight out of *Star Trek* are the metamaterial “cloaking devices” invented by Pratt engineers. The devices, which have received worldwide publicity, render objects invisible to waves—electromagnetic waves from microwaves to visible light, as well as sound waves.

David Smith—who began his metamaterial research before the term even existed—has led in the theory and design of such cloaking devices. In 2006, he and his colleagues demonstrated the first cloaking device, which made objects disappear in the microwave spectrum. The device was basically a group of concentric circles of printed circuit board, designed to coax microwaves to flow around an object placed in the middle, rejoining on the opposite side. When the scientists placed a copper cylinder in the middle, it “disappeared” in the microwave region of the spectrum.

The group’s major achievement, however, came in 2009 when they reported a cloaking device that could potentially render objects invisible to a range of electromagnetic waves, from radio waves to visible light. The cloak’s construction was more challenging than that of the microwave cloak, because the elements for such devices must be smaller than the wavelength to be cloaked. So the rectangular device, measuring 20 inches by 4 inches by less than...
leads projects to build such devices, emphasizing those for submillimeter waves, telecommunications, and optical applications.

“What our group has done—aside from these benchmark experiments—is to create a computational approach that allows us to take any structural component and create a physical model that describes its macroscopic properties as if multiple such components were combined as a larger material.”

Beyond cloaking, the algorithms they developed will enable custom-design of a wide range of complex metamaterials, including those that can focus and redirect electromagnetic waves for a variety of purposes. As director of the Pratt Center for Metamaterials and Integrated Plasmonics (CMIP), Smith

an inch high, consisted of more than 10,000 individual pieces of circuit board etched with copper, arranged in parallel rows.

In their experiments, the researchers aimed a beam of microwaves through the cloaking device at a “bump” on a flat mirror. The waves reflected from the mirror as if the bump were not present, cloaking it. The device also suppressed the scattered beams that would normally arise from such a bump.

As dramatic as these demonstrations were, it is the theory behind them that has the broadest implications, says Smith. The experimental devices demonstrated that the researchers could apply the algorithms they developed in the theoretical field of “transformation optics” to design metamaterials with a wide range of properties. For Smith, the devices proved their theory with gratifying success.

“What our group has done... is to create a computational approach that allows us to take any structural component and create a physical model that describes its macroscopic properties as if multiple such components were combined as a larger material.”
with the old version is that it focused from one spherical surface to another, rather than onto a flat plane, so Smith and his colleagues designed and constructed a planar, flattened Lüneburg lens out of metamaterials that focuses onto a flat plane.

In another demonstration of diffractive optics, the group created, designed and built an infrared metamaterial hologram. Looking like a set of miniature venetian blinds, the design of the three-dimensional hologram could be adapted to produce holographic images at a range of wavelengths.

The applications of such metamaterial devices are vast, encompassing “really any device that has to do with electromagnetics. At low frequencies products could include superior antennas; in the infrared and visible they could include light sources, detectors and modulators,” says Smith.

For example, the researchers have engineered smaller, more efficient lenses for auto collision avoidance systems. And Yaroslav Urzhumov, working in the Smith lab, created a metamaterial “superlens” that could enable transmission of wireless electric power over distances of many feet. This capability could solve a major drawback of electric cars, the long charging time, by enabling the vehicles to recharge themselves while driving in charging lanes whose pavement is embedded with the lenses, basically thin loops of copper on a fiberglass substrate. Similarly, such superlenses might also enhance the efficiency of power transfer to magnetically levitating trains.

Urzhumov and Smith have extended their metamaterial development to water waves. They envision a metamaterial shell around a ship’s hull that could enormously streamline the flow of water around it. The proposed “fluid flow cloak” would consist of a porous plate fitted with tiny pumps that could push flowing water along.

“The goal is to make it so the water passing through the porous material leaves the cloak at the same speed as the water surrounding the vessel,” says Urzhumov. “In this way, the water outside the hull would appear to be still relative to the vessel, thereby greatly reducing the amount of energy needed by the vessel to push vast quantities of water out of the way as it progresses.”

Steven Cummer, who has worked with Smith on electromagnetic cloaking, has created the acoustic analog of transformation optics—“transformation acoustics.” Using that theory, he has built cloaking devices that make objects invisible to sound waves.

Because sound comprises wavelengths much longer than light, Cummer’s devices are much larger in scale than optical cloaks, resembling very sophisticated plastic Legos. Thus, Cummer and his colleagues can conveniently produce their components using 3D printing.

With this technique, they have constructed acoustic cloaks for both water and air. The water cloak, he believes, could be applied to render ships and submarines invisible to sonar while the air cloak could prevent sound, vibration, or seismic waves from penetrating structures or spaces. In sound applications, a cloaking material could improve concert hall acoustics by making beams and other sources of interference “disappear” from the hall’s acoustic signature.
Theories describing the properties of nanoparticles, metamaterials and other nanodevices would constitute little more than an intellectual exercise unless they could actually be built. To transform theory into functioning devices, some 500 researchers from Duke and other institutions turn to the Shared Materials Instrumentation Facility (SMIF). The 11,000-square-foot complex, directed by Nan Jokerst, houses clean rooms containing dozens of instruments for constructing and characterizing devices and materials. These include an electron beam lithography system, a plasma enhanced chemical vapor deposition instrument, a robot for cryogenically freezing specimens, an atomic force microscope, and an array of spectrometers.

And in a highly unusual juxtaposition, SMIF also includes a “bio clean room” for integrating biological materials with nanomaterial, optical, and electronic devices and structures. “It’s where soft, wet biomaterials meet hard, solid dry materials,” says Jokerst.
Overall, she says, SMIF “enables us to develop processes and build and optimize metamaterials and other devices that few other places can produce.” These might include metamaterials consisting of hundreds of layers engineered at a nano-scale.

Jokerst has collaborated with Smith and his colleagues to create numerous metamaterial devices based on their theories. For instance, she led the fabrication group that constructed the metamaterial hologram and the planar Lüneberg lens. She is also working with Smith and SensorMetrix Corporation, the company he cofounded with colleague Tony Starr, to tackle practical manufacturability issues. For example, she says, “When we build these multilayer perfect absorbers, how sensitive is the performance to the dielectric layer thickness? To the lateral misalignment between the layers? To the rounding of the corners of features that theoretically should be sharp? To the width of the feature?” Answering such fabrication questions will help bring metamaterials rapidly to the marketplace, she says.
A thousand-megapixel camera zooms way way in

Not only have David Brady and his colleagues invented a camera with a thousand times greater resolution than the usual digital camera, they have created a camera that they believe can be scaled down to handheld size and sold at an affordable price.

To capture the vast amount of data in a gigapixel image, they engineered their camera to incorporate multiple cameras. Behind a central objective lens sit 98 microcameras, each of which captures the detailed images of a small area in the field of view. These images are stitched together by a computer algorithm to form a single database that comprises the gigapixel image.

While the prototype is about the size of a mini-refrigerator, the electronics can readily be reduced to make a handheld camera, says Brady. And while the prototype only produces black and white images, future versions will feature multispectral imaging and enhanced optical properties such as depth of field. The researchers are also working toward thousand-fold higher resolution terapixel (million-megapixel) images.

Other gigapixel images have been produced, but they have taken many minutes to capture. In contrast, the Duke camera takes images very rapidly, and the researchers are now building a camera that can take ten images a second. Ultimately, they hope to reach a video frame rate.

At the camera’s ultra resolution and high frame rate, such images cannot be displayed or printed, says Brady. Rather, they can constitute an image database that users can “mine”—for example, by a sports fan choosing which view of a game to zero in on.

Besides such commercial applications, government agencies could use such cameras to monitor sites such as military bases or even entire cities at high resolution in real time, says Brady. And, the cameras could be used with wide-field telescopes to image in unprecedented detail objects such as hazardous space junk in orbit.

Beyond their gigapixel cameras, Brady and his colleagues in the Duke Imaging and Spectroscopy Program (DISP) are developing a wide range of imaging and spectroscopy instruments. These operate at visible, infrared, ultraviolet, x-ray, millimeter wave, terahertz, and acoustic wavelengths. For example, for the Department of Homeland Security they are developing x-ray imaging instruments that enable rapid, high-resolution detection of explosives.

The researchers have also achieved advances in image processing techniques such as “compressive tomography.” In this technique, they have demonstrated that it’s possible to reconstruct a three-dimensional image—in the visible, millimeter-wave or radar spectrum—using only a single two-dimensional frame of data. ■
Quantum computing: re-inventing the “transistor”

While metamaterials and gigapixel cameras might find their way to the marketplace in only years, quantum computers are still only conceptual. However, Jungsang Kim and his colleagues are tackling the major technical challenges of engineering the integrated circuit-equivalent of the quantum computer capable of processing large numbers of qubits. Such qubits operate far below the scale of the transistor, at the atomic level.

Developing a quantum computer could have profound implications for data security, by allowing financial institutions to create the ultimate uncrackable code. Quantum computers could bring unprecedented power to search vast, unstructured databases—an overwhelming task analogous to attempting to identify a person in a phone book when given only a phone number.

Kim is principal investigator of the multi-university Modular Universal Scalable Ion-trap Quantum Computer (MUSIQC) Program, which aims to build a large-scale quantum computer, possibly up to 80 qubits. To date, such computer structures have been limited to a few qubits. Besides Duke, collaborators also include researchers from Georgia Tech, University of Maryland, University of Michigan, University of British Columbia, University of Washington, and University of Sydney.

The group is concentrating on a quantum computer where qubits consist of atomic ions trapped in a vacuum chamber. The state of the ion is controlled by a laser beam, and together the system constitutes an atomic-level switchable device. There are many competing quantum computer approaches that rely on solid-state devices using superconducting circuits or quantum dots, but, says Kim, the trapped ion system provides pristine qubits on which the most reliable quantum information processing is currently possible. The race is on for various quantum computer approaches to construct scalable quantum processors, starting with tens of qubits, but eventually containing up to thousands of interconnected qubits.

In MUSIQC architecture, a large number of small quantum registers are connected using an optical interconnected network to achieve a scalable quantum processor. Kim and his colleagues are developing new technologies to tackle this problem, such as complex ion traps made using the same approach used to build silicon computer processors, and tools to steer the laser beams to precisely and reliably control the state of the trapped ion. Integration of such control is critical in constructing a multi-qubit computer circuit.

Another major challenge being tackled by Kim and Duke physicist Dan Gauthier is capturing the data held in a trapped ion and converting it into light pulses that can travel over optical fibers. They are working with researchers from the University of Maryland, University of Michigan, Stanford, Uni-
versity of Illinois, University of California San Diego, National Institute of Standards Technology, and Naval Research Laboratory as part of a collaboration funded by the Army Research Office.

Such conversion is critical if quantum computers are to communicate with the outside world or with one another. Computers shift information from one form of physical representation to another all the time, such as voltages in transistors on a computer chip, radio waves on a wireless router, or pulses of light in the internet backbone to get across the continent. Inter-computer connection is just as important for quantum computing and communication because, while quantum dot computers might have higher processing speed, trapped-ion computers would be a better storage medium, Kim says.

The problem the researchers face in such communication is that trapped ions emit photons in the ultraviolet range, but optical transmission requires light at longer infrared wavelengths. To solve the problem, they are engineering so-called “nonlinear optical materials” that can accomplish such conversion. The researchers are also creating what is called a “quantum temporal imaging system” to enable the two kinds of quantum computers to communicate with one another. Such systems would translate the picosecond-long timescale of absorptions and emissions of quantum dots into the nanosecond timescale of trapped ion systems. These technologies might one day enable quantum internet where quantum computers are connected through fundamentally secure communication links.

Once they are successful in their efforts, quantum computers may well join cloaking metamaterials and gigapixel cameras on the list of impossible machines invented at the Pratt School. ■
Mikkelsen builds a research bridge with physics

In her research on quantum dots and photonic devices, new assistant professor Maiken Mikkelsen’s joint appointment in Pratt’s Department of Electrical and Computer Engineering and Duke’s Department of Physics represents a critical research bridge between the two departments. Her interdisciplinary work could enable significant advances both in basic physical understanding of those devices and in engineering photonic systems to shrink from the micro- to the nanoscale.

For example, she is trying to understand how quantum dots, which can function in computing as quantum bits, or qubits, could be coupled to form optical computers. Her work also encompasses the engineering of plasmonic materials—that is, metamaterial composites of metallic and dielectric materials that can achieve optical properties not seen in nature. Such materials could serve as waveguides in quantum dot systems.

Her work also aims at overcoming resolution limits associated with the wavelength of light and enabling scientists to “see” DNA molecules rather than merely “feeling” them with atomic force microscopes, as is common now. As a postdoctoral fellow at the University of California at Berkeley, Mikkelsen and her colleagues achieved the first demonstration of plasmonic “lenses” that could be key to such advances.

Mikkelsen received her M.A. and Ph.D. in physics from the University of California at Santa Barbara. Her thesis won the 2011 European Physical Society’s Ph.D. Thesis prize, Quantum Electronics and Optics Division.
Both these machines—the heavenly solar sail and the hellish turbine—present complex research challenges in “aeroelasticity” being tackled by three Pratt school experts. Aerospace engineers Earl Dowell, Kenneth Hall, and Robert Kielb have spent decades developing methods to analyze aeroelastic forces. Engine designers and aerospace engineers are using their insights to design machines as disparate as solar sails and the turbines that power just about all electric generating plants, airplanes, and windmills.

The solar sail being designed by NASA is among the most exotic of these devices. Such solar sails are attractive for spacecraft propulsion because they carry no conventional fuel, using only the pressure of sunlight to propel them. In their work, Dowell and graduate student Chad Gibbs, along with colleagues at NASA Langley Research Center, are analyzing a potential oscillation in what Dowell has dubbed the field of “solarelasticity.”

“This is a kilometer-sized sail, and because solar pressure is very small, the material has to be very thin,” says Dowell. “But if you make it thin and you make it very flexible, the same solar pressure that moves it along is also large enough to induce oscillations; and these oscillations are analogous to what happens due to the fluid forces in more conventional craft.”

At the other extreme of spacecraft engineering Dowell and his graduate student, Ben Goldman, are helping analyze the aeroelastic performance of a new form of reentry vehicle called HIAD (hypersonic inflatable aerodynamic decelerator). HIAD describes an assembly of high-strength inflatable bladders, like a stack of inner tubes, meant to protect and slow down a spacecraft from the searing 3,000-degree Fahrenheit temperatures during
reentry to the earth or other planets.

Dowell’s latest aircraft project is just as exotic—a giant solar-powered airplane called Vulture, designed to cruise slowly at high altitudes for years at a time. The unmanned airplane being developed by Boeing for DARPA could circle above areas of interest much longer than drones, carrying a payload of high-resolution cameras.

With its 400-foot wingspan, twice that of a Boeing 747, the lightweight Vulture could be highly vulnerable to wind gusts, so Dowell and his colleague, Deman Tang, and his students are analyzing such wing behavior in wind tunnel testing and computational studies.

Dowell and his graduate student Ivan Wang are also working on the aeroelastic problems presented by so-called “morphing” wings—which fold into different shapes to adapt to different flying conditions. Like a bird’s wing, they could yield much greater efficiency over the broad range of speeds at which aircraft operate. However, with this morphing advantage come complex problems of flutter and other phenomena that need to be solved before airplanes can fly more like birds.

Finally, the flutter of high performance aircraft such as the F-16 and F-35 are still challenges to aeroelastician Jeff Thomas and graduate student Madhu Padmanabhan who are working with Dowell and the Air Force to address. Mike Balajewicz is completing his Ph.D. studies of turbulence and a novel method of constructing models for this complex nonlinear dynamical system that has drawn the attention over many years of investigators including such luminaries as Werner Heisenberg, G.I. Taylor and Theodore Von Karman.

While flutter is a problem in aircraft wings, it is absolutely necessary for a very different aeroelastic research challenge—a “nonlinear aeroelastic energy harvesting” system that Dowell is helping develop, along with former undergraduate Jared Dunnmon, who is now a Rhodes Scholar at Oxford, and Gibbs. This wind energy approach uses a flexible airfoil designed to oscillate in the wind, with the oscillation energy converted to electricity by piezoelectric material connected to it.

“This system has some real attraction because you don’t have to worry about tuning the system’s natural frequency to the wind as do so-called resonant systems” says Dowell. “You just need to exceed a certain wind speed. And that speed can be very low.” While the wind-harvesting system won’t offer the high output of conventional windmills, says Dowell, it would be useful for low-power applications in remote areas.

Dowell’s latest research advances represent only the latest in a long line of achievements that have earned him the major awards in his field, including the Daniel Guggenheim Medal Award of multiple professional societies, the Den Hartog Award of the American Society of Mechanical Engineering, the Spirit of St. Louis Award of the American Society of Mechanical Engineers and the Distinguished Service Award of the American Academy of Mechanics, as well as membership in the National Academy of Engineering and Honorary Fellow of the American Institute of Aeronautics and Astronautics.
Bad vibrations

While the wind system depends on flutter, for Kielb and Hall, flutter and other vibrations are an anathema in turbines. Currently, the engineers are concentrating their research on a particularly mysterious phenomenon called “non-synchronous vibration”—refining computational models that turbine designers can use to minimize its effects.

Non-synchronous vibration is distinct from the other two major categories of turbine vibration—“force response” and “flutter.” Force response arises in multi-blade turbines when the wake from one turbine blade exerts forces on a downstream blade. And flutter is a “self-excited” vibration of the blades. But non-synchronous vibration in turbine blades arises from instabilities in the air itself.

“In such a case, the air is the primary source of the instability, and it couples with the blades in what is known as fluid/structure interaction,” says Hall.

Explains Kielb, “Buildings, bridges, and airplane wings have natural frequencies at which they like to vibrate, and if you force them with those frequencies then they oscillate at high amplitude. But a phenomenon that is much less understood is the natural frequencies that fluids also have. For example, if you blow on the top of the Coke bottle you can hear the air vibration inside the bottle.”

Non-synchronous vibration presents two kinds of bad news for turbine designers, say Kielb and Hall. First, says Kielb, it is becoming more and more a factor as engine designs push the envelope in conditions and materials.

“The temperatures have gone up, the pressures have gone up, the speed has gone up, the thickness of the material has gone down, and the weight has gone down,” says Kielb. “As we push these limits, we discover that we cannot accurately predict the non-synchronous vibrations that will arise.”

The second piece of bad news—and a major reason Kielb and Hall are focusing so intently on non-synchronous vibration—is that it can create blade fractures that don’t even show up until the engines are being tested; and redesign is extremely expensive.

“Our experience is that half of the compressors that have been developed over forty years have had some form of this phenomenon,” says Kielb. “Many times when there was such a problem, the design would be changed until it went away, but we didn’t know why. We really need to understand this, and not just change a design and just hope it goes away.”

To provide such support, Kielb heads a center at Duke for a consortium called GUIde 4—for “Government Agencies, Universities, and Industry working together on a common goal.” The group sponsors research on turbine blade vibration and fosters transfer of the findings to industry. GUIde 4 includes NASA, the Air Force Research Laboratories, the major engine manufacturers, and six other universities besides Duke—Arizona State University, MIT, Penn State University, Purdue University, Texas A&M University and the University of Miami.
Simplifying design simulations

Reducing the massive complexity of programs that perform computational fluid dynamics (CFD) simulations is another major goal of work by Kielb, Hall, and Dowell. Such simulations are critical to turbine design, yet they can take months for even the most powerful computer to grind through.

Says Kielb, “Of course, industry would like to have design iterations in a matter of hours, or at least days. They put pressure on researchers like us to give them methods to design their engines quickly, not only because it’s cheaper, but the faster they can do them, the more analyses they can do.”

To remedy the problem, the Pratt engineers are creating “reduced order” modeling tools to enable engine designers to perform preliminary computational “scouting” missions to understand where they need to concentrate more detailed modeling firepower, “so rather than making a few hundred CFD runs maybe you could do ten. And that saves them a lot of money and time in developing engines,” Kielb says.

Says Dowell, reduced order modeling “can take a very large mathematical system of millions of equations and reduce it down to tens or maybe a few hundred. That has some computational advantages but it also is easier for us to understand a smaller system than the behavior of that large system.”

Adds Hall, “It’s a way of distilling out the important features which hopefully will reduce the computational costs.”

Turbine design will continue to advance for many decades to come, and so will the complexity of the engineering problems, says Kielb. So a robust supply of new engineers will be needed to meet such research challenges.

To educate those engineers, the school’s mechanical engineering and materials sciences department participates in the international turbomachinery aeromechanics master’s program called THRUST, funded by the European Union. In the program, the department partners with the Swedish Royal Institute of Technology, the Aristotle University of Thessaloniki in Greece, and the University of Liège in Belgium. It enables students to earn degrees from multiple institutions, taking advantage of their courses and facilities. According to Kielb, the graduates are being snapped up by airplane and engine manufacturers, and increasingly the wind energy industry.
New bioengineering and materials science professor Jennifer West is developing nanoshells whose structure is “tuned” to absorb a wavelength of infrared light at which body tissues are relatively transparent. This transparency makes the nanoshells ideal as light-activated tumor killers.

The nanoshells consist of a thin layer of biologically inert gold with a silica core. Once in a patient’s bloodstream, they tend to accumulate in tumors, because of tumors’ leaky vasculature. When infrared laser light is shone on the tumors, the nanoshells heat up and destroy the tumor. The nanoshells are already in clinical trials for prostate tumors and recurrent head and neck tumors, conducted by Nanospectra Biosciences, Inc., a company founded by West.

West is also devising bioactive polymers called hypergels that can mimic the extracellular matrix that cells produce in tissues. These hypergels can be used as the medium for growing bioengineered cells for tissue engineering. They can also be designed to coat arteries to release nitric oxide, an anti-clotting chemical, to speed healing after angioplasty and as an interior coating for artificial grafts.

West comes to Pratt from Rice University. She holds 15 patents which have been licensed for commercialization. Her awards include 2010 Texas Inventor of the Year, a Rice University J.M. Chance Prize for Excellence in Teaching, the 2003 MIT Technology Review’s selection of 100 Top Young Innovators Award, and designation as a Howard Hughes Medical Institute Professor.
Inventing machinery that is soft, wet... and living

Pratt’s engineers are developing biomaterials to repair the body and kill cancers

Farshid Guilak wants to construct a replacement for a load-bearing part on a machine in continuous service for more than half a century. The corroded part is allowing critical surfaces to grind against one another, causing severe damage. It’s a one-of-a-kind component, needing custom-fabrication. Guilak’s solution is to scan the worn part while it works inside the machine and use a 3D printer to shape a mold for the replacement. From that mold, he casts a framework for the part and infuses it with microscopic factories that, once installed, will grow the functioning part.

Similarly, Nenad Bursac seeks to engineer a booster for a damaged pump, also continuously functional for decades. Replacement of the whole pump is expensive and difficult, so he constructs a contractile patch that, when installed, will reinforce the faltering pump’s function.

Charles Gersbach faces the challenge of finding and fixing a subtle programming error that threatens destruction of the entire system. Previous efforts to correct the errant code failed because they didn’t pinpoint the bug. Gersbach uses a targeting technique that locates the coding mistake with unerring precision, and corrects it.

Guilak, Bursac, and Gersbach aren’t mechanical or computer engineers, but biomedical engineers. They exemplify Pratt’s research success in applying engineering analysis and fabrication, not to factories or computer networks, but to the living body. Guilak’s work aims to replace damaged cartilage in hips and knees; Bursac’s to rescue failing hearts; and Gersbach’s to correct genetic malfunctions.
They and their colleagues approach diseases such as osteoarthritis, cancer, diabetes, heart disease, and hemophilia as engineering challenges. They are creating tools and treatments to understand and correct all these “malfunctions.”

Understanding and restoring diseased joints

Guilak and his colleagues are animal-testing 3D hip implants comprising a mesh of the same polymer used in sutures that are resorbed into the body. They create the mold for this implant by feeding data from an MRI scan of the joint into a 3D printer. Once they use the mold to create the implant, they seed the mesh with stem cells that, once in the body, will generate cartilage that replaces the damaged tissue.

Their greatest challenge is generating cartilage-forming stem cells. Guilak is producing such cells by culturing fat cells with chemicals to transform them. In another approach, with colleague Kam Leong, he is generating the cartilage stem cells from what are called “induced pluripotent stem cells.” In a third approach, he is working with Gersbach to genetically “edit” stem cells, to induce them to produce cartilage.

He is also developing a quick-isolation technique that does not involve expensive and time-consuming culturing of cells. In this method, the researchers isolate cartilage-generating stem cells at the time of surgery, so they can be quickly infused into an implant.

In basic studies, Guilak focuses on how obesity causes arthritis. He is discovering surprising evidence that the disease does not necessarily arise from increased joint load. For example, he says, obese people have more osteoarthritis in their hands, which don’t bear loads. Rather, his human and mouse studies indicate that obesity leads to a chronic inflammation from production by fat cells of inflammatory chemicals called cytokines.

“This insight can be quickly applied to the clinic,” says Guilak. “We’re planning studies of people with joint injuries, in which to reduce arthritis, we change their diet—first of all to lose weight, but also to lose fat and thus reduce inflammation.”
Mending a broken heart

Bursac is developing methods to grow patches of cultured cardiac muscle to rejuvenate damaged hearts. He believes such tissue patches may well have significant advantages over the method currently in clinical trials—injecting stem cells to treat heart disease. Indeed, researchers have found evidence in animal tests that patch implants do add the pumping power of healthy muscle to the faltering heart. But a major challenge he and his colleagues are tackling is engineering such patches to have blood-carrying vasculature.

“The holy grail of tissue engineering is to grow perfusable active vasculature in the tissue, because that would allow you to make big, thick slabs of tissue, or even a whole organ,” he says. So in their animal studies, Bursac and his colleagues are studying techniques to rapidly induce vascularization in an implanted cardiac patch. They are creating pores in the tissue and attempting to promote blood vessel growth using chemical factors, or electrical and mechanical stimulation.

The engineers in Bursac’s group are also working at the cellular level to generate cells that conduct electrical impulses as efficiently as do the heart’s original cells. Lacking such rapid conduction, cellular or tissue implants could generate arrhythmias. In one culture technique, skin cells are genetically reprogrammed to revert to more immature stem cells, and then matured into cardiac muscle cells. In another technique, skin cells are directly engineered to become implantable electrically conducting cells.

In cultured cardiac cells, they seek to achieve natural velocities of electrical propagation by applying electrical and mechanical stimulation to mimic conditions in the beating heart. So far, he says, the laboratory has developed cells that in culture can achieve conduction velocities similar to those measured in adult rat heart. They are also culturing skeletal muscle, both as a research tool—to screen drugs and explore cell genetics—and someday to replace muscle tissue damaged by trauma or disease.

Creating biosynthetic electrically active cells from skin cells is another aim of Bursac’s research. While cultures of actual neurons or heart cells are difficult to maintain, the biosynthetic electrically active cells are easy to culture and genetically tinker with. These altered cells conduct electrical signals much like actual neurons or heart cells and can help to understand the biological machinery of electrically conducting tissues.
Delivering cancer drugs naturally

Because cancer drugs are basically poisons, that happen to affect cancer cells more than normal cells, researchers are seeking ways to precisely target them to tumors, sparing healthy tissues.

Drug-delivery systems are being tested that use metal nanoparticles or synthetic polymers, but these may be potentially toxic foreign substances once they deliver their cargo. At Pratt, Ashutosh Chilkoti has developed a uniquely benign nanoparticle cargo carrier that consists of a non-toxic, biodegradable polymer closely resembling elastin, a connective tissue protein. The polymer is engineered to automatically assemble into nanoparticles when linked to cancer drug molecules.

The nanoparticles can also be designed to “melt” and release their drug cargo in the low pH environment of tumors. Thus an aberrant property of tumors, compared to normal tissue, can be used as a trigger to release a toxic drug dose.

Chilkoti and his colleagues have also invented a mass-production technique for synthesizing large libraries of genes that code for a range of elastin-like polymers that can greatly aid the search for more effective polymers. Called the “overlap extension rolling circle amplification method,” it will enable scientists to easily create gene libraries not only for elastin, but for collagen, silk, and other structural proteins for use in biotechnology, tissue engineering, drug delivery, and biosensing.

They have also invented “protein microarrays” that, like DNA microarrays, could be used for cheap, rapid analysis. With such they can rapidly test saliva, blood, or urine for proteins indicating disease.

To create the arrays, the researchers grow a “forest” of a polymer on a chip. When dried, the polymers readily grab hold of and permanently trap antibodies. Scientists can create patterned microarrays of such antibodies by using an inkjet printer to spray the antibodies onto the chip. By using antibodies that selectively attach to disease-related proteins, researchers can create a chip that is a highly sensitive detector of the protein.
Poisoning cancer’s food

David Needham has a new strategy for killing tumors—smuggling cancer drugs into the cancer cells hidden in lipids, their primary energy source.

Needham is already a pioneer in developing heat-activated liposomes for killing tumors. These tiny lipid droplets, when engineered to contain cancer drugs, are taken up by tumors because of their leaky vasculature. The liposomes are engineered to release their cargo when heated, killing tumor cells.

Needham’s new cancer-killing concept is to engineer artificial particles of low-density lipoprotein (LDL) to contain cancer drugs. In contrast to untargeted liposomes, LDL has surface proteins that attach to specific receptors on the cell surface to be taken into the cell. Since cancer cells are prodigious consumers of lipid, they would absorb LDL, and with it, the cancer drug.

LDL’s specificity means that the drug-carrying lipids could target the diffuse cancer cells of metastatic disease, in which the cancer has spread throughout the body, says Needham.

“So, the issue now is to reverse-engineer nature’s design of LDLs to figure out how to build them and how to incorporate cancer drugs.”

Needham and his colleagues have invented a process they call “microglassification” to deliver another class of drugs—those composed of protein. The technique could be applied to formulate protein drugs that cost less to produce and are easier to deliver, says Needham.

Microglassification involves using the organic solvent decanol to dry proteins into glasslike microbeads, whose size can be controlled by adjusting the parameters of the drying. The process is fast and requires no special equipment. The technique preserves the protein structure and function, in contrast to the used protein preservation process of freeze-drying, which can damage sensitive biologic drugs.

Leading collaborations to create biomaterials

Inventing new biomaterials is an interdisciplinary quest, so Pratt engineers lead three broad-based centers to foster such development.

The Triangle Materials Research Science and Engineering Center (MRSEC), directed by Gabriel Lopez, aims to be a national resource for research and education in materials science and engineering. In particular, MRSEC collaborators are developing techniques to produce self-assembling structures of “soft matter”—that is, the kinds of polymers, colloids, and other macromolecules typically found in living cells.

The center was launched in September 2011 and is funded by the National Science Foundation. Besides Duke, MRSEC academic participants include North Carolina State University, North Carolina Central University and the University of North Carolina-Chapel Hill. Participating government laboratories include Oak Ridge National Laboratory, Los Alamos National Laboratory, the National Institute of Standards and Technology, and Sandia National Laboratories. MRSEC sponsors public education through a partnership with the North Carolina Museum of Life and Science.
To create artificial tissues and organs, engineers will need to provide the cells a biodegradable scaffold to temporarily support them as they form the final structure. Leong and his colleagues are developing such “microenvironments,” discovering the crucial role that their topography plays in how cells differentiate. They are finding that nanoscale features such as nanopores and nanoridges can profoundly influence cell morphology.

Leong and his colleagues are also engineering DNA nanoparticles to genetically alter cells—using the nanoparticles to transform stem cells into neuronal cells. The nanoparticles consist of a positively charged polymer, which when mixed with negatively charged DNA molecules, automatically forms a nanoparticle.

While other groups use viruses to transport DNA into cells, “a nonviral approach would be safer, because you wouldn’t have to worry about the effects of viral components in the transformed cells,” says Leong.

He is already developing a clinical application for his DNA nanoparticles—altering liver cells to produce coagulation factor to treat hemophilia. In the first demonstration of oral gene delivery by nonviral methods, his experiments with mice have shown that oral administration of the nanoparticles can produce coagulation factor in circulation.

The Center for Biologically Inspired Materials & Material Systems (CBIMMS) includes some 30 Duke researchers and nearly 20 collaborators at other institutions or companies. Headed by Chilkoti, besides Pratt engineers CBIMMS includes Duke chemists, biologists, and physicists who “reverse engineer” nature to learn to create tools and devices for practical application, such as nanosensors for environmental and clinical use.

The Center for Biomolecular and Tissue Engineering (CBTE), which includes researchers from Pratt, Trinity College, and the medical center, aims to link three broad areas of biotechnology: protein engineering, cellular engineering, and tissue engineering. In protein engineering, CBTE researchers designed targeted proteins and shorter peptides that can be used to elicit specific cell responses and to develop targeted drug therapies. The center’s research in cellular engineering seeks to develop techniques to regulate cells to improve drug and gene delivery and to support tissue engineering. Tissue engineering work in the center aims at designing and modifying materials that will support and foster growth of artificial tissues for therapeutic treatments.
Opening the way for coronary arteries, blood sensors

Artificial coronary arteries don’t work. The tubes invariably clog with clots because they are so small. However, if they could be made clot-resistant, they would be sturdier than natural veins and arteries now harvested for bypass surgery, and wouldn’t necessitate an additional operation to harvest a vein or artery. William Reichert is working with George Truskey and Bruce Klitzman to develop techniques to avoid clotting by seeding the surface of artificial grafts with endothelial cells that will coat the graft with a clot-resistant layer.

In studies with rats, they have found that immature cells (endothelial progenitor cells) implanted in artificial arteries will grow into a clot-resistant barrier. And in new experiments, they are using Leong’s tissue-engineering technology to grow living arteries and test their sturdiness and clot-resistance.

Reichert is also tackling the body’s “protective” clotting reaction to implanted glucose sensors used to control insulin pumps in diabetes. The sensors are largely ineffective because clots form around them triggering scar tissue formation that encapsulates the sensors.

Reichert and his colleagues are analyzing the biology behind the encapsulation and testing whether they can minimize it and enhance blood flow by infusing the sensors with drugs that trigger blood vessel formation or reduce inflammation. They are also testing whether sensors with anti-clotting surface textures might prevent encapsulation.

Pratt biomedical engineers have achieved a unique series of honors in being awarded Society for Biomaterials Clemson Awards in 2010, 2011, and 2012.

In 2010, William “Monty” Reichert was given the Clemson Award for Basic Research, which honors work that has “conferred to the basic knowledge and understanding of the interaction of materials with tissue.” The award is given for that work that is “evidenced by significant research, important original publications in the literature and/or frequent reference to and reliance on this work by subsequent researchers.” Reichert received the award for his work in functionally accurate in vitro assays for biomaterials.

In 2011, Ashutosh Chilkoti received the Clemson Award for Contributions to the Literature. This award is given for distinction in publishing in scientific journals, and frequent citations and referencing of the work by others. Chilkoti was honored for his publications on interfacial phenomena in biomaterials.

In 2012, Kam Leong won the Clemson Award for Applied Research, which honors “development of a useful device or material which has achieved widespread usage or acceptance.” Leong was honored for his invention of novel materials for controlled drug delivery, particularly Gliadel, a biodegradable wafer for delivering anti-cancer drugs for brain cancer therapy that has been used in the treatment of thousands of patients worldwide.
Engineering materials inspired by biology

Gabriel Lopez is seeking to solve a problem shared by the human body and oceangoing ships—biofouling. A ship immersed in salt water attracts proteins, which in turn attract bacteria and organisms such as barnacle larvae. Similarly, when the body encounters an implant or sensor, proteins immediately stick to it, attracting cells that ultimately coat it. Lopez and his colleagues are analyzing how the proteins that trigger biofouling stick to the surface of medical implants as well as ship hulls.

“Biofouling is becoming a bigger and bigger clinical problem as there are more implants and because of the rise of drug-resistant bacteria,” says Lopez. “So we are exploring new ways to control the attachment of bacteria to surfaces, such as designing them to be deformable.”

Also inspired by biology is Lopez’s work with the Materials Research Science and Engineering Center (MRSEC) (see sidebar, page 28) to help create materials that include self-assembling proteins and colloids. In forming such structures, researchers first use heat or a magnetic or electric field to induce molecules to assemble themselves. Lopez’s role is to figure out how to fix these structures in place by encapsulating them and integrating them into hybrid materials.

Such materials could have unique optical or acoustic properties. For example, says Lopez, they could replace expensive indium tin oxide as the transparent conductive coating in solar cells and flat panel displays. MRSEC researchers are also working on self-assembling nanowires for ultrasmall circuitry.

“We are exploring new ways to control the attachment of bacteria to surfaces, such as designing them to be deformable.”

Using sound waves to isolate cells is another major, and very different, focus of Lopez’s research. In this technology, the researchers selectively tag target cells with polymer particles that react to sound waves. When they impose a standing acoustic wave on the cell mixture, the tagged cells separate from the mixture by being pushed to one point in the acoustic field. The researchers can then collect the cells for analysis. In the clinic, the acoustic technology could be used as a diagnostic or therapeutic tool, says Lopez. It would uniquely enable physicians to isolate rare cancer cells, stem cells, or other progenitor cells from blood.
Finding and fixing aberrant genes

Gersbach seeks to overcome a major drawback of gene therapy—the lack of specificity. He and his colleagues are developing "genome editing" techniques that find and repair disease genes as well as "genetic reprogramming" techniques to transform cells into new types.

The current gene therapy approach of inserting a corrected gene into a cell is "like having a car with a burned out headlight, and rather than replacing the headlight, just adding an extra one somewhere on the car," says Gersbach.

In contrast, Gersbach is synthesizing versions of a targeting enzyme that can specifically recognize a faulty stretch of DNA in a disease gene. It binds to the site and directs the cell to replace the genetic error with the correct sequence.

Gersbach and his colleagues have laboratory-tested their editing technique by restoring function in the gene that causes Duchenne muscular dystrophy using muscle cells from patients with the disease. Next, they plan to begin testing the treatment in mice.

In their genetic reprogramming work, they are exploring how to alter a cell’s genetic regulatory machinery to transform easily accessible cells such as skin cells into muscle, bone, cartilage, blood vessel, or heart cells. They have genetically reprogrammed skeletal muscle cells to repress the muscle cell genes and switch on those that produce bone cells. As a result the muscle cells transformed into bone-forming cells that could be used to regenerate bone.

They have also developed a unique approach to controlling gene activity using ordinary light. While scientists have long used chemicals such as antibiotics or steroids to control genes, those techniques introduce a foreign substance that can trigger unwanted, or even toxic effects.

To achieve light control, the researchers engineered light-sensitive proteins from plants into a gene-targeting enzyme called a "zinc finger protein," so that the system could be adapted to switch on and off just about any gene. They found in experiments with human cells, that the altered protein could be an effective genetic "light switch." According to Gersbach, the light control system could constitute a basic tool to explore how genes function in cells. It could also be used to precisely control genes in cells that produce biopharmaceuticals such as cancer drugs.
Spying on DNA repair

Although the structure of DNA has been known for half a century, Piotr Marszalek’s research has yielded new surprises about the mechanics of the molecule’s behavior, insights that not only advance basic understanding of DNA, but how it reacts to damage from sources like radiation.

Marszalek and his students use atomic force microscopy (AFM) to stretch a single strand of artificial DNA, while precisely measuring the force required. In their experiments, they stretched a synthetic DNA strand called polyadenine, a chain of flat adenine molecules stacked like pancakes. They expected the strand to extend smoothly like a rubber band. Instead, they found that the molecule alternately stuck and stretched, indicating unknown internal structures that were being uncoupled.

“We found that this behavior was fully reversible, and that it was the signature of breaking the stacking interactions between the adenines. Our measurements represent a contribution to fundamental knowledge of the forces that stabilize the helix.” Such knowledge aids in understanding the intricate DNA replication process, which involves unwinding and separation of double-stranded DNA, says Marszalek.

The researchers also used AFM to measure the forces needed to mechanically separate subunits of a protein called streptavidin. Such measurements are important, says Marszalek, because streptavidin may be easily attached to other proteins. So it could serve as a “hub” for construction of self-assembling protein nanomaterials with tailored mechanical properties.

Marszalek has also used AFM stretching and imaging techniques to study how both UV light and gamma rays damage DNA. In those experiments, he blasted DNA with UV light and studied the formation of internal crosslinks in the DNA. The studies revealed that UVa light, which is considered safer than UVb, did cause damage. The gamma ray studies were important because gamma radiation is central to cancer radiation therapy, notes Marszalek.
Sapiro brings a new vision to Pratt

From creating “smart” MRI scanners that automatically distinguish tumors, to scanning a roomful of children for behaviors that portend autism, Guillermo Sapiro’s research quite literally brings a new vision to the Pratt School. He arrives at the school from the University of Minnesota.

Sapiro has published more than 200 peer-reviewed papers and is the founding editor-in-chief of the SIAM Journal on Imaging Sciences. In 2010, he was awarded the National Security Science and Engineering Faculty Fellowship, which is awarded to distinguished scientists and engineers to conduct basic defense-related research.

He uses image-processing techniques to render MRI scans more effective as diagnostic tools and decrease scanner time. Reduced scanner time makes MRI more useful for squirming toddlers or Parkinson’s patients, for whom holding still during a scan is extremely difficult.

Sapiro is also building smart imaging into consumer devices like mobile phones. Such imaging would enable a user to take a photo or video of, for example, the Eiffel Tower, and the phone would automatically tag it. Thus, such automatic tagging could enormously aid organization of the zillions of images posted on the internet daily.

His software can also analyze video to decipher people’s movements to infer their behavior. For example, a smart video screening system could detect the characteristic repetitive movements of autism, identifying children at risk of the disorder, enabling therapy to begin earlier.

He is also creating algorithms to recognize patterns in text. For example, his laboratory is developing techniques to do “sentiment analysis” on Twitter messages—to distinguish whether, for example, the tweeter is happy or sad about a topic being tweeted.

Given the breadth of applications of his work, Sapiro says he expects no shortage of collaborators from Pratt and the medical center.

“When I first interviewed here for two days, I saw perhaps twenty-five faculty,” he recalls. “And each of them gave me three or four more names that should have been on my list. I could have spent a full week just meeting potential collaborators!”
Things great and small: environmentally responsible nanotechnology

Pratt engineers aim to protect the environment while preserving the bottom line

They are called “mesocosms,” the dozens of crates filled with soil, water, plants, and fish. Basking in the sunlight of a Duke Forest clearing, they might seem ordinary. But the crates are actually sophisticated ecological experiments that exemplify Pratt’s comprehensive approach to exploring the environmental impact of nanomaterials. The mesocosms—continuously monitored by a network of sensors—seek to mimic the intricate ecology of microbes, plants, and animals that comprise wetlands. By dosing the mesocosms with nanomaterials—manmade particles a millionth the size of a grain of sand—Duke researchers can trace the subtleties of their transformation and movement through the model ecosystem.

The mesocosms are part of the Duke-led Center for the Environmental Implications of NanoTechnology (CEINT). The aim of this multi-institution center is to assess the potential environmental impact of a technology before it becomes widespread, not after. Other CEINT academic participants include Carnegie Mellon University, Howard University, Virginia Tech, Stanford University, and the University of Kentucky.

The foreknowledge of the impact of nanomaterials that arise from CEINT research will guide industry in developing new environmentally benign products, as well as assess the effects of those already on the market. But CEINT, sponsored by the National Science Foundation (NSF) and the Environmental Protection Agency (EPA), has broader objectives, says director Mark Wiesner.
“At CEINT, we are not just addressing the nano problem but really creating the template for how one does research on the emerging implications of new technologies,” he says. Thus CEINT could influence the fundamental philosophy by which industry develops the vast range of new products entering the marketplace.

Importantly, CEINT operates synergistically with the Superfund Basic Research Center headquartered in the Nicholas School of the Environment. Headed by the Nicholas School’s Richard Di Giulio, the National Institute of Environmental and Health Sciences (NIEHS)-sponsored center conducts a broad range of research into the effects of toxic chemicals on the environment and human health. It includes researchers from across Duke’s campus, including those from the Pratt School.

According to Wiesner, these two centers exemplify the collaborative strengths that give Pratt’s engineers such an ideal environment to study the environment. “To do productive work in environmental engineering, you really need to have access to a broad range of expertise, and Duke has it all—the environmental chemists, the environmental toxicologists, the environmental lawyers, the environmental engineers, and the environmental economists,” he says.
Helping the environment and industry

CEINT’s “ahead-of-time” study of nanomaterials will not only preserve the environment, but also the bottom line of the companies making them, emphasizes environmental engineer Desiree Plata, who heads Pratt’s Laboratory for Integrated Technology Ecologies (LITE).

The traditional, all-too-often disastrous approach has been for companies to invest heavily in developing new materials with little analysis of their environmental impact. Often, a company launches a product into the marketplace then materials or by-products find their way into the environment. This can lead to deleterious environmental impacts that require expensive filtering, cleanup, and litigation. Such has been the case with many industrially important chemicals, including dioxins, PCBs, pesticides, asbestos, and the gasoline additive MBTE.

However, Plata and her colleagues are using nanomaterials as a model to show how integrating up-front environmental impact analysis into product design can guide the process. The resulting product will not only be inherently environment-friendly, but should yield a far longer revenue stream by avoiding such costs as post-release cleanup or fines.

“I think the ‘us-versus-them’ mind-set has failed historically, and it will continue to fail. We need to be at a place where we are actually working together with industry to innovate sustainability. We’re also incorporating this approach into our undergraduate engineering curriculum, by trying to train responsible engineers who are serving a greater purpose and hopefully finding fulfillment in that,” Plata says.

Plata and her fellow environmental engineers are also helping companies make their existing manufacture of nano-products both cleaner and more efficient.

“We asked the people making nanomaterials ‘have you ever looked at the end of the tailpipe of this reactor, and do you know what’s coming out?’” Plata and her colleagues developed analyti-
cal techniques, and not only identified methods to help clean up the tail pipe, but offered insights into the mechanisms that form such molecules as nanotubes.

“We were able to reduce the emissions by orders of magnitude,” she says. “And we were also able to reduce the energy costs by half and reduce the input requirements by between twenty and forty percent depending on the processes. So that translates into cost savings for the company.”

environmental benefits.

“The farmer can now sell renewable energy and carbon credits, which are in higher and higher demand. And the farmer could even get paid for taking in other agricultural residues, food waste and chicken manure, for example, and converting them into renewable energy in his anaerobic digester. This is potentially a transformational shift in the farming business model.”

Deshusses and his students are also exploring the far larger global problem of treating human waste. Supported by the Bill & Melinda Gates Foundation project to reinvent the toilet, they are designing a self-contained human waste reactor for third-world countries lacking sewer connections or even septic treatment. Their toilet will use anaerobic digestion to break down human waste, and use heat from generated biogas to sterilize the waste, thereby limiting the spread of disease-causing germs. The treated waste could also be used as a fertilizer.
Understanding mercury toxicity at the nano scale

Heileen Hsu-Kim believes that before scientists can solve the big picture issue of protecting people and the environment from the harmful effects of mercury, they need to see the small picture.

A very small picture.

She would like to figure out exactly what happens when naturally-occurring or man-made mercury first reaches the sediments on the bottom of oceans or lakes and then gets taken in by a microbe. For her, this is the key step in the process that ultimately finds the microbe being eaten by a larger organism, and then another, all the way up the food chain—with the mercury accumulating each step of the way.

“We all know that certain forms of mercury are toxic and what they can do living things,” says Hsu-Kim, assistant professor of civil and environmental engineering and recent awardee of a Presidential Early Career Award for Scientists and Engineers (PECASE). “But we don’t totally understand the processes within the sediments that create the dangerous forms of mercury, a process known as methylation.”

“Before we can develop effective remediation strategies for mercury, we really need to see what happening at the nano-scale,” she says.

Hsu-Kim plans to spend the next few years teasing out all the subtle biochemical reactions that occur in the sediments leading to the methylation of mercury.

“This information will ultimately be used to establish a new geochemical framework for predicting mercury methylation potential in contaminated sediments,” she says, ushering in a new field she terms “nano-geochemistry.”

Wiesner wins 2011 Clarke Award for research excellence

In 2011, Mark Wiesner was awarded the Athalie Richardson Irvine Clarke Prize for excellence in water research—consisting of a gold medallion and a $50,000 award. Wiesner was afforded the honor for “his groundbreaking efforts and leadership in improving water quality through advancements in membrane and nanotechnology research.” The award is given by the National Water Research Institute.

In addition to serving as director of the Center for the Environmental Implications of NanoTechnology (CEINT), Wiesner is the James L. Meriam Professor of Civil and Environmental Engineering. Nanomaterials—in the form of membranes, adsorbents, and catalysts for water treatment—hold high promise for water treatment and groundwater remediation. However, as Wiesner declared in his Clarke Prize Lecture, “our challenge is to ensure that nanotechnology evolves as a tool for sustainability rather than as an environmental liability.”
Lee Ferguson works with carbon nanoparticles, and as part of CEINT, has developed analytical techniques to solve the first problem in understanding their environmental impact—detecting them. Metal nanoparticles are relatively easy to detect by searching for the metals. “So when we want to analyze metal nanoparticles in sediments, or soils, or organisms, we are looking for a needle in a haystack,” says Ferguson. “But since carbon nanotubes are made of the same material as sediments and tissues of organisms, looking for them is like looking for a piece of wheat in a haystack.”

Fortunately, single-walled nanotubes show a distinctive fluorescent spectrum under near-infrared light. So Ferguson and his colleagues have developed a fluorescence analytical technique that has enabled them to detect one ten-millionth of a gram of carbon nanotubes in a gram of sediment.

The critical next step is to understand the biological impact of these concentrations, and Ferguson is working with ecotoxicologist Thomas Chandler at the University of South Carolina to do such analysis. Chandler studies the effects of the nanotube concentrations, while Ferguson measures the kinds of tiny crustaceans called copepods that live in sediments of estuaries. They are the equivalent of canaries in the coal mine because nanomaterials in the environment tend to associate with sediments. Chandler is studying the nanoparticle effects on the creatures’ development and reproduction.

Ferguson’s and Chandler’s nanotube analyses are only the latest in a long line of environmental studies. They have developed techniques to analyze the concentrations and biological impact of pesticides and other compounds that mimic estrogens in the environment. These so-called “endocrine disruptors” are known to have a profound and widespread impact on organisms.

“An increased production of nanomaterials will likely lead to the introduction of these materials into natural waters and ecosystems, with unknown consequences. In addition to any direct environmental impacts from nanomaterials, potential exists for environmental degradation stemming from waste byproducts and energy or materials usage associated with nanomaterial production, use, and disposal.”

Citing nanomaterials as “just one example of a continuous stream of technologies that require the proactive evaluation of possible impacts on human health and ecosystems,” Wiesner said that “such evaluations are fundamentally a public good that must be nurtured by the public sector to ensure not only the safety, but also the advancement and commercialization, of emerging technologies.”
Nano-surprises and nano-mysteries

Studies by engineers working in CEINT have yielded important scientific insights into the environmental impacts of nanomaterials, says Wiesner. Those studies include not only laboratory studies such as Ferguson’s on organisms and cells, but those using the mesocosms. The combined studies have yielded some surprises.

“We’ve had cases where the lab produces results showing more toxicity than you get in the field, which is kind of what I would have expected. But we’ve also shown cases where lab studies predict lower toxicity than what we find in the field, which I would not have guessed.”

One key finding from the mesocosms, he says, is that nanoparticles can “bioaccumulate,” that is, they can enter organisms and pass through the food chain, perhaps becoming concentrated.

The particles can also undergo complex transformations in the environment, the researchers have found. They may combine with organic matter or other chemicals to form larger particles. Or they may become coated with a natural substance that increases not only their longevity in the environment, but possibly their impact as well. Wiesner cites nanomaterials used in medicine as an example of such transformations.

“We have shown that the nanomaterials that come out of the factory aren’t necessarily the ones that you need to worry about,” he says. “For example, if a nanomaterial was being used to deliver drugs, once it’s injected, it is covered in protein, and such modification can have unforeseen consequences.”

Whether such transformations occur in the environment or in the body, they can change nanomaterials’ inherent toxicity and reactivity, says Wiesner.

Environmental engineer Claudia Gunsch is exploring a potential Jekyll-and-Hyde property of nanoparticles. Silver nanoparticles are widely used as antimicrobial agents to treat such products as clothing, surgical instruments, bandages, and food storage containers. However, these nanoparticles might literally cause a downstream problem when they enter wastewater.

Gunsch is testing the effects of different silver nanoparticles on nitrifying bacteria that transform nitrates in wastewater, preventing them from becoming pollutants that would create algae blooms and eutrophication in streams and lakes. Wide use of the silver nanoparticles might even thwart their own effectiveness, says Gunsch.

“We expect to find silver-resistant bacteria, which would produce much the same problem as antibiotic-resistant bacteria have,” she says. “That could present serious problems in using these nanoparticles as antimicrobials.”

The studies by Pratt engineers don’t seek to test the environmental fate of every possible nanoparticle, says Plata, given that the industry is innovating so rapidly. Rather, the aim is to test a range of nanoparticles, to develop a fundamental understanding of their properties and enable scientists—from industry, government, or academia—to predict the impact of new types.

According to Wiesner, such knowledge can help create a system for assessing risk that will both reveal environmental threats and guide product development.

“As we gain knowledge about these materials, we can build mathematical tools that can predict the risk they might pose, and that we can adapt as new data comes in,” he says. “This ability to do these kinds of calculations will be a critical step in both avoiding environmental impact and helping companies develop more benign products.”
SPOTLIGHTS

Maiken Mikkelsen
Assistant Professor, Electrical and Computer Engineering

See Faculty Spotlight, page 16.

Guillermo Sapiro
Professor, Electrical and Computer Engineering

See Faculty Spotlight, page 34.

Jennifer West
Professor, Biomedical Engineering

See Faculty Spotlight, page 22.

Wilkins Aquino
Associate Professor, Civil and Environmental Engineering

His research interests encompass general computational mechanics, inverse problems and their applications in engineering and biomedicine, coupled chemomechanical problems, and scientific computing, among others.
His doctoral research utilized principles and techniques from soft matter physics to study cellular mechanical properties. He developed a genetically encoded, calibrated molecular tension sensor capable of visualizing molecular force across specific proteins in living cells and plans to combine these research areas to determine the mechanisms cells utilize to sense and respond to the mechanical nature of their microenvironment.

Guglielmo Scovazzi
Associate Professor, Civil and Environmental Engineering

Recognized as one of the leading young researchers in computational mechanics, his work is breaking new ground in applied mathematics and through its application solving pressing problems in both solid and fluid mechanics such as subsurface carbon sequestration, wind turbine blade design, and hydraulic fracturing for natural gas extraction.

Michael Zavlanos
Assistant Professor, Mechanical Engineering and Material Sciences

Specializes in the area of networked dynamical systems and distributed control, with applications to robotic, sensor, biomolecular, and social networks. In February 2011, he was recipient of a NSF Faculty Early Career Development (CAREER) Award.
“It’s critical that we continue to invest in the fields and in the people who will shape the world’s future.”

- JEFFREY VINIK
The Viniks give $10 million for Duke faculty who engage with engineering challenges

Alumnus Jeffrey N. Vinik and his wife Penny have given Duke $10 million to establish a faculty challenge fund that will be used to hire and retain professors who focus on complex societal challenges in engineering and related areas of energy, global health, brain sciences and the environment.

The Vinik Faculty Challenge Fund, a dollar-for-dollar matching fund, will be leveraged to create up to 10 full or associate professorships dedicated to addressing problems that affect quality of life. Many of the faculty will have primary appointments in the Pratt School of Engineering while others will be jointly appointed between Pratt and another school or institute at Duke to foster interdisciplinary collaboration.

“The problems facing society today create immense opportunities for students who are capable of bridging their science and engineering education with complementary skills in economics, humanities and policy,” Vinik said in a news release. He went on to say, “Duke has a very strong engineering program and some of the brightest and most talented professors and students in the world. It’s critical that we continue to invest in the fields and in the people who will shape the world’s future.”

A Phi Beta Kappa graduate of Pratt, Vinik earned a bachelor of science in 1981 and received an MBA from the Harvard Business School in 1985. Formerly the manager of Fidelity Magellan, Vinik is the founder of the Boston-based Vinik Asset Management. He owns the National Hockey League’s Tampa Bay Lightning and Arena Football League’s Tampa Bay Storm, and is a minority owner of Major League Baseball’s Boston Red Sox. His wife, Penny, is actively involved in several nonprofit organizations in the Boston area, including the Museum of Fine Arts Boston and the Meadowbrook School, where she was chair of the board for five years.

In recognition of their gift, the deanship of the Pratt School of Engineering has been named in honor of the Viniks.
“Preparing Duke engineering graduates to be leaders and innovators in the 21st Century workforce who use knowledge in the service of society.”

- PRATT EDUCATION MISSION
### Pratt Undergraduates

- 30% Women
- 11% Underrepresented minorities
- 92% Graduate in four years
- 90% Have an intensive research experience or an industry internship
- 30% Have an international experience

NAE Grand Challenges Scholars program began at Duke in 2009; now in development at more than 40 top engineering schools across the United States

### Pratt Graduate Students

- Launched new Master of Engineering programs in 2011
- Graduate enrollment has increased from 274 to 436 since 2008
- Ph.D. Plus Enhancement program launched in 2012 is one of the first in the country to offer entrepreneurship and professional training for Ph.D. students
GROWTH IN RESEARCH

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>$25.8 million</td>
</tr>
<tr>
<td>2003</td>
<td>$48 million</td>
</tr>
<tr>
<td>2004</td>
<td>$49.3 million</td>
</tr>
<tr>
<td>2005</td>
<td>$55.4 million</td>
</tr>
<tr>
<td>2006</td>
<td>$59.7 million</td>
</tr>
<tr>
<td>2007</td>
<td>$63.6 million</td>
</tr>
<tr>
<td>2008</td>
<td>$67.8 million</td>
</tr>
<tr>
<td>2009</td>
<td>$69.9 million</td>
</tr>
<tr>
<td>2010</td>
<td>$84 million</td>
</tr>
<tr>
<td>2011</td>
<td>$90.1 million</td>
</tr>
</tbody>
</table>

YEAR FACULTY

<table>
<thead>
<tr>
<th>Year</th>
<th>Faculty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999/00</td>
<td>89</td>
</tr>
<tr>
<td>2000/01</td>
<td>95</td>
</tr>
<tr>
<td>2001/02</td>
<td>94</td>
</tr>
<tr>
<td>2002/03</td>
<td>100</td>
</tr>
<tr>
<td>2003/04</td>
<td>105</td>
</tr>
<tr>
<td>2004/05</td>
<td>111</td>
</tr>
<tr>
<td>2005/06</td>
<td>115</td>
</tr>
<tr>
<td>2006/07</td>
<td>117</td>
</tr>
<tr>
<td>2007/08</td>
<td>116</td>
</tr>
<tr>
<td>2008/09</td>
<td>118</td>
</tr>
<tr>
<td>2009/10</td>
<td>113</td>
</tr>
<tr>
<td>2010/11</td>
<td>125</td>
</tr>
</tbody>
</table>

PRATT PRIDE

2 Rhodes Scholars
3 Marshall Scholars
6 Goldwater Scholars
7 Fulbright Scholars
2 Churchill Scholars

Pioneers of 3D Ultrasound techniques used around the world in every medical specialty
First accredited biomedical engineering program in the U.S.
Inventors of landmine and explosive device detection techniques used by the military
First to explain the mechanics of DNA spiral shape