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"I believe that nanomedicine will be where the biggest opportunities for nanotechnology will be found a decade from now. The potential for increased longevity that nanotechnology seems to present to us, coupled with the aging population seems to be an irresistible force, always assuming that nanomedicine can live up to its potential."

—Lawrence Gasman, NanoMarkets, LC



Improving health and longevity.

This issue of the Foresight Nanotech Update focuses on Foresight Nanotechnology Challenge #3, Improving health and longevity. We have invited experts to offer their ideas on how nanotechnology will impact health and medicine. Medical advances based on nanoscale research are receiving significant amounts of attention and funding. The opinions presented in this issue represent a cross section of researchers who are focusing on diagnostics, preventive medicine, cancer treatment or longevity.

We hope you find this issue of the Foresight Nanotech Update informative.

Foresight Nanotechnology Challenges:

1. Providing renewable clean energy
2. Supplying clean water globally
3. Improving health and longevity
4. Healing and preserving the environment
5. Making information technology available to all
6. Enabling space development

Good for people. Good for the planet.

Foresight Nanotech Institute was founded 20 years ago to prepare society for nanotechnology. A central theme to our activities is the continued belief that nanotechnology will be a powerful force to improve the health and well being of people and the planet.

Today, nanotechnology is no longer an idea. Nanotechnology is becoming a fundamental force that will offer major rewards for the humanity in fields ranging from biotech to energy. This technology will have a tremendous impact on our society. Foresight is dedicated to fostering nanotechnologies that can make a significant contribution to solving critical challenges which humanity currently faces.

The Foresight Nanotechnology Challenges were created to encourage dialogue and pinpoint areas where nanotechnology could fulfill its promise of being good for people and good for the planet.

Medical Experts Q&A:

Anita Goel, MD, PhD

Nanobiosym Labs / Nanobiosym Diagnostics, Inc.



"I am betting on portable diagnostics. I have already placed my money on and time into it. I believe in it. I want to see this technology delivered to the world."

Anita Goel, MD PhD
President and Scientific Director, and Chief Executive Officer
Nanobiosym Labs / Nanobiosym Diagnostics, Inc.

We know that there are some nanotech applications that are moving towards the approval process. Which treatments do you think will be approved and in use the soonest?

This is hard to predict. I think that diagnostics and targeted therapeutics are the low hanging fruit. I think nanotech will enhance those areas first. There are likely to be several nanotech approaches in other areas as well that will allow things to be done from the bottom-up in a faster, cheaper and better fashion.

How soon will we see the impact of nanotechnology in health and medical devices?

In my field of interest, diagnostic devices, I am hoping a 3-5 year timeframe, but it may be longer. My company, Nanobiosym Diagnostics, is working on building nanoscale devices as a platform to enable rapid point-of-care diagnostics.

How do you see nanotechnology changing the cost of and access to medical care in the future?

Well, my personal vision is handheld diagnostics available to everyone. This would be a device that patients could have in their homes. It would also be appropriate for the developing world, where many human beings do not have access to testing for diseases. Right now, if you suspect an infection, the blood is drawn. It is then transported to a testing facility and the results are available in a few days, maybe weeks later. Meanwhile, the disease continues to spread.

Handheld diagnostic tools could make a great difference during times of national pandemics. It would allow us to have rapid response capabilities for several scenarios. This nanotech platform would radically impact our ability to diagnose and respond quickly to stop the spread of infection during bioterrorist attacks or disease outbreaks similar to SARS.

If you look at the paradigm shift in the telecommunications industry when communications and computing became portable, I believe a similar shift will happen in health care when our diagnostic capabilities move from the pathology lab to the portable "lab-on-a-chip" that nanoscale research will enable.

What are the concerns, if any, related to nanotechnology applications in the field of medicine, health and longevity?

With every new technology, including nanotechnology, there should be some responsible content and consideration on how the technology is deployed. Nuclear technology is neither good nor bad. It is how we apply it, energy versus weaponry, which defines it.

Nanotechnology is a new field and people need to be careful and responsible. We need to develop our ethical side and keep conscious of how to manage the technology as we go hand-in-hand with its development.

Do you see any public or policy conflicts, such as equal access debates, resulting from increasing health and longevity through nanotechnology?

Conflict may arise from who controls the technology platform and who holds the technology. While we will be driven to make a profit from this technology, it is critically important for us to develop our ethics and humanitarian aspect as we go. That is where organizations, such as Foresight, can help because they raise society's general awareness and help educate the public about this developing technology.

If you were in the office pool, which nanotech medical solution would you put your money on to make the biggest impact in the future?

I am betting on portable diagnostics. I have already placed my money on and time into it. I believe in it. I want to see this technology delivered to the world. It will make a huge difference in patient care throughout the world.

How do you see your current research impacting nanotechnology and medicine in the future?

My commercial goal is a low-cost, handheld device that can give people worldwide instant access to their own diagnostic information. Of course, there are some other biodefense and biomedical applications along the way. On the R&D side, we have a few fundamental projects under incubation at the crossroads of physics, biomedicine, and nanotechnology.

Physicist and physician, Anita Goel, MD, PhD was recently named one of the world's "top 35 science and technology innovators under the age of 35" by MIT's Technology Review Magazine. Dr. Goel holds both a PhD in Physics from Harvard University and an MD from the Harvard-MIT Joint Division of Health Sciences and Technology (HST) and BS in Physics from Stanford University.

Dr. Goel is the President and Scientific Director of Nanobiosym Labs and the President and CEO of Nanobiosym Diagnostics, Inc. Nanobiosym Labs focuses on fundamental research at the interface of Physics, Medicine, and Nanotechnology. Nanobiosym Diagnostics, Inc. is the commercial arm of Nanobiosym that is developing next-generation diagnostic capabilities. Dr. Goel's work at Nanobiosym has been recognized by recent prestigious funding awards from the United States Department of Defense and DARPA and US Dept of Energy.

She is a Fellow of the World Technology Network, a Fellow-at-Large of the Santa Fe Institute, and an Associate of the Harvard Physics Department.

Medical Experts Q&A:

Mansoor M. Amiji, RPh, PhD

Bouve College of Health Sciences /
Northwestern University



"I hope that nanotechnology provides an opportunity for prevention, early disease diagnosis, and patient-specific therapeutic approaches. In the end, not only should we emphasize longevity, but also improve the quality of life."

Mansoor M. Amiji, RPh, PhD
Professor and Associate Department Chair
Bouve College of Health Sciences / Northwestern University

We know that there are some nanotech applications that are moving towards the approval process. Which treatments do you think will be approved and in use the soonest?

There are a number of approved nanotech products and many are in clinical studies being conducted with platforms that have a high degree of safety, such as liposomes, nanoemulsions, and polymeric nanoparticles. These, in my opinion, will be approved within the next few years.

These nano-platforms are especially necessary for the imaging and therapy of cancer and cardiovascular diseases. Additional products with more sophisticated technologies, such as those with combination therapies, imaging and therapeutic modalities, and the use of nanoshells for ablation, will come to the market.

For the future, getting more nanotech products to the market will depend on pharmaceutical and medical device companies' willingness to invest in these technologies for preclinical and clinical studies. Adequate resources from these companies are necessary in order to move the technologies beyond academia and small start-ups.

How soon we will see the impact of advanced nanotech in health and medical devices?

The timeline depends very much on the type of technology and the potential use. Nanotechnology-based diagnostic devices and imaging systems will be the first to make the impact. Work done in Dr. Mirkin's group at Northwestern, Dr. Lieber's group at Harvard, and Dr. Heath's group at CalTech will clearly lead in the development of technologies for early disease diagnosis and predictive medicine. Molecular imaging systems, such as those developed in Dr. Weissleder's group at Mass General and others, are also going to transform medicine to a great extent. In the therapeutic side, combination products using more sophisticated technologies, such as remote controlled delivery systems, use of nanoshells for ablation, etc., will prove cutting-edge.

(Continued on page 6)

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— Jillian Elliott
President, Foresight Nanotech Institute

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Medical Experts Q&A:

Donald A. Tomalia, PhD

Dendritic Nanotechnologies, Inc.



"Perhaps the greatest reason for being excited about nanotechnology research is that it provides society an opportunity to examine new options for solving old problems."

Donald A. Tomalia, PhD
President and Chief Technical Officer
Dendritic Nanotechnologies, Inc.

We know that there are some nanotech applications that are moving towards the approval process. Which treatments do you think will be approved and in use the soonest?

There is one product that our parent company is involved with that is expected to be approved in the relative near future. This product is VivaGel, a topical, vaginal microbicide that is designed to prevent the transmission of sexually transmitted diseases including HIV and genital herpes. This product is moving into the final phases of approval with the FDA.

We are hoping that by the end of next year or 2008 at the latest that this product will be approved for human use. It is a dendrimer based nano-pharmaceutical that is applied topically and used by females. Once we receive approval for the HIV topical, which will be used by females, we will already be on the fast track for clinical trials for FDA approval on a topical that prevents the transmission of genital herpes.

Starpharma acquired my company, Dendritic Nanotechnologies Inc. (DNT), in October 2006. The combined expertise of the two companies, Starpharma and DNT, is expected to provide a synergistic environment for designing and advancing dendrimer based nanotech products for the prevention and diagnosis of disease to market more quickly.

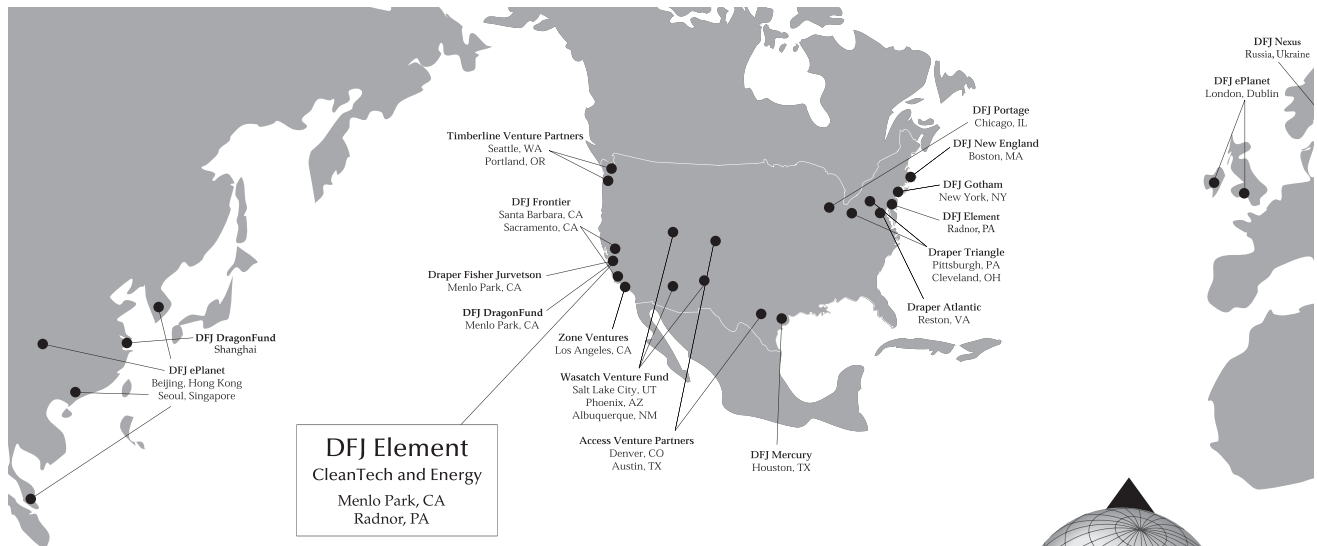
How do you see nanotechnology changing the cost of and access to medical care in the future?

I believe that, if a defined nanotechnology solution to a medical problem is simple and cost effective, such solutions often provide new options and benefits. For example, the HIV preventative that is being worked on at Starpharma has the potential to be a relatively low cost treatment; while the gains in prevention will be immeasurable. The medical costs for treating AIDS patients are enormous. Being able to prevent these types of diseases will have an immediate impact on the high cost of health care and hospitalization.

Another issue regarding the cost of health care is how we are currently treating life threatening diseases such as cancer. Presently, most traditional chemotherapy treatments involve "whole body" exposure to an oncology drug leading to

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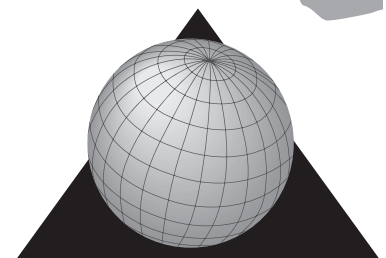
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tremendous, peripheral damage and terrible side effects when treating cancer. New drug delivery strategies, using dendrimer based nano-containers and nano-scaffolding, allow one to deliver a variety of very toxic cancer therapy drugs which can be targeted to the specific disease site and released, thus reducing side effects. We expect to be able to use such targeting strategies for both diagnosis and the treatment of a variety of diseases. Such nano-based medical treatment is expected to provide a patient with a higher "quality of life" and allow them to be more useful to society.

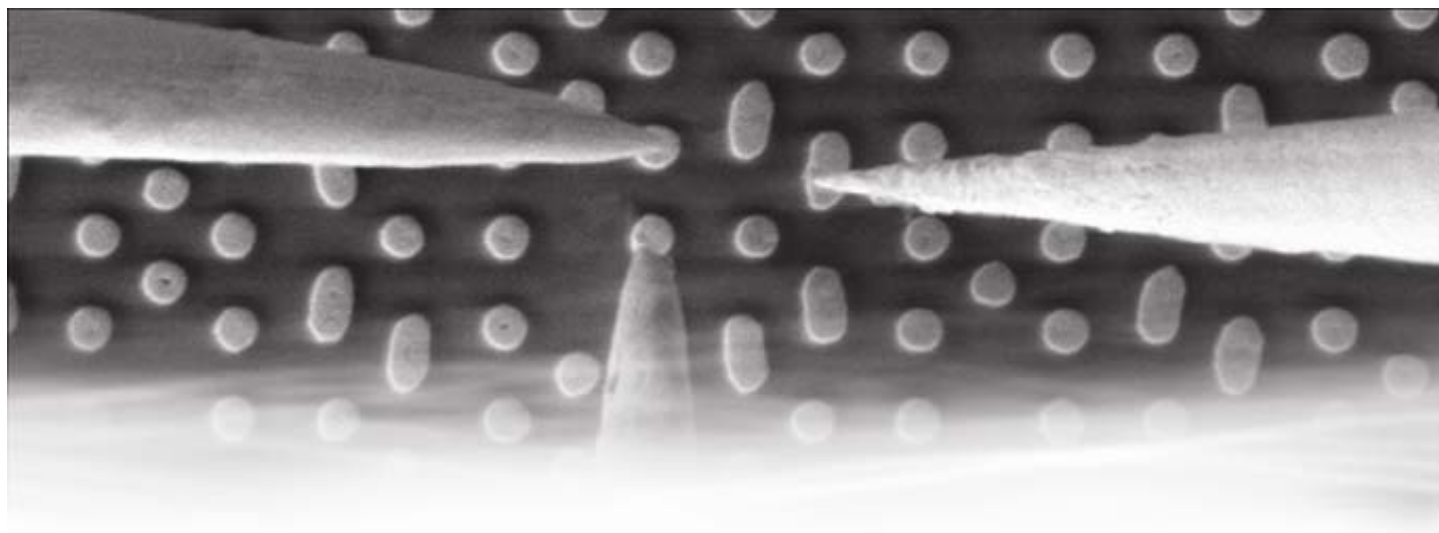
What are the concerns, if any, related to nanotechnology applications in the field of medicine, health and longevity?

I recently served as chair of an EPA panel that was charged with providing a peer review of the EPA's "Nanotechnology White Paper." The panel consisted of qualified experts representing the entire spectrum of nanotechnology stakeholders. The general consensus was that the responsibility for defining appropriate nanotechnology, risk/benefit boundaries would require the same use of credible and systematic scientific principles that were used for traditional physics and chemistry. New adaptations of analytical and characterization methodologies may be required to define any new nano- properties, patterns or rules as the field evolves. We have worked extensively with "dendrimers" for the past twenty years. They are widely recognized as precise, "bottom-up" synthesized nanostructures ranging from 1nm to

50nm in diameter, represented by over 100 known compositional families and more than 1000 different surface chemistries. We have developed many new synthetic, analytical, biological and pharmacological methodologies based on these unique organic nanostructures which have stood the test of time and re-examination as evidenced by over 8000 published references to date. This area of nanotechnology has been pursued largely by traditional well established scientific principles and to date has produced no alarming negative surprises. Just as these scientific principles and methodologies have served us so well for our traditional chemistry disciplines for the past 200 years, I am confident that such a systematic scientific approach will provide us with appropriate means for assessing realistic risk/benefit boundaries an adequate safety margins.

Of course, there could be abuses in nanotechnology, especially if the researcher does not properly characterize and understand the chemical/physical features or potential hazards of their nano materials. These new, non-traditional nano properties sparked the revolution and nanoscientists undoubtedly expect to find additional unique "hierarchically driven" properties as our field matures. However, it will also be our responsibility to address these properties properly and look for the positive benefits that these new features may bring to important social issues such as medicine, health and longevity as they are weighted against any risk boundaries. Perhaps the greatest reason for being excited about nanotechnology research is that

(Continued on page 9)



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How do you see nanotechnology changing the cost of and access to medical care in the future?

Initially, newer medical technologies tend to always cost more. However, as progress continues, I think the overall cost of medical care will be substantially lower as early diagnosis will require less intense and expensive therapy, use of targeted delivery systems will require less dose and will have less side effects, and the cost of hospital stay will decrease as more treatments will be done in an outpatient basis.

What are the concerns, if any, related to nanotechnology applications in the field of medicine, health and longevity?

Safety of nanotechnology is the biggest cause for concern. Researchers need to be more informed of the biological interface that these technologies will have to interact. Attention must be paid to the understanding of bio-distribution and clearance of the nanotechnology products, if they are meant to translate into human therapies.

What do you anticipate as the greatest benefits of nanotechnology in the field of medicine, health and longevity?

I hope that nanotechnology provides an opportunity for prevention, early disease diagnosis, and patient-specific therapeutic approaches. In the end, not only should we emphasize longevity, but also improve the quality of life.

Do you see any public or policy conflicts, such as equal access debates, resulting from increasing health and longevity through nanotechnology?

Absolutely, I think as history has shown, there will be debates about access, healthcare costs, as well as the potential environmental impact of nanotechnology. However, these are all important issues that as a society we should consider, discuss, and embrace.

If you were in the office pool, which nanotech medical solution would you put your money on to make the biggest impact in the future?

Improving drug therapy by overcoming biological barriers and disease-specific localization is an area that is near and dear to me. I believe there are many candidate drug molecules that could benefit from the use of nanotechnology.

(Continued on page 17)

Foresight Nanotechnology
Challenge #3:
Improving health and longevity



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Nanomedicine

By Robert Freitas



“The key practical issue with medical nanorobotics is: what will it take to build these devices? The answer is that it will take an efficient molecular manufacturing system.”

Robert Freitas
Senior Research Fellow
Institute for Molecular Manufacturing (IMM)

How soon we will see the impact of advanced nanotechnology in health and medical devices?

Nanomedicine involves three conceptual classes of molecularly precise structures: nonbiological nanomaterials, biotechnology materials and devices, and nonbiological devices including medical nanorobotics. It is only the third area -- devices and nanorobots -- that really qualifies as "advanced" nanotechnology.

We could see medical microrobots (extensions of today's automated lab-on-a-chip systems) over the next 5-10 years, it will probably be the 2020s before the first true nanorobots can be fabricated. The earliest devices will be very simple. Most likely they will be used primarily for diagnostic purposes, and usually *ex vivo* or on the outermost surfaces of the body. Any kind of *in vivo* application, whether diagnostic or therapeutic, will require more extensive testing to obtain FDA approval. This takes time. So the answer is that we will start to see some impact of medical nanorobotics during the 2020s, but the impact will rise rapidly after that. My view is that medical nanorobotics **is** the future of medicine in the 21st century. Nanorobots are the only means by which certain procedures can be done -- for example, repairing widespread physical trauma, performing individual cell repair, or rapidly rebuilding organs and tissues *in situ*. In other medical applications where competing technologies may exist, nanorobots will be faster, better controlled, safer, and more convenient to use than those other technologies.

There are still some people who opine that nanorobots cannot possibly work. However, the specific objections that are raised have invariably been addressed long ago in the technical literature. This is not to say that all possible operational problems involving medical nanorobots have been solved. They haven't, not by a long shot. But certainly the most significant and obvious problems have been raised, discussed, and potential solutions proposed. Yes, a lot more research remains to be done. But critics should at least read the technical literature before criticizing the concept of medical nanorobotics.

For example, I often see critics questioning aspects of the biocompatibility of nanorobots. Some apparently believe that nobody else has ever thought of these issues before. But there is an entire technical book (Nanomedicine, Vol. IIA) with 6000+ literature references on the subject of nanorobot biocompatibility. There's no excuse for critics not having read it (or electronically searched it) as it is freely available on the web at <http://www.nanomedicine.com/NMIIA.htm>. The reason I spent years writing this book was to encourage nanorobotics to be taken seriously by the scientific community. If critics intend their objections to be taken seriously, then they should read the relevant literature that discusses their point of concern and then point out any technical flaws in that discussion if they can. Anything less is intellectually dishonest.

The key practical issue with medical nanorobotics is: what will it take to build these devices? The answer is that it will take an efficient molecular manufacturing system. One straightforward system of this kind would be a desktop nanofactory. The long-term goal of the recently-launched Nanofactory Collaboration (<http://www.MolecularAssembler.com/Nanofactory>) is to work towards a design, and ultimately to build, a functioning diamondoid nanofactory. Such a nanofactory would be able to build diamondoid medical nanorobots in therapeutically useful quantities.

While some work has been done on each of the four primary capabilities believed necessary to design and build a functioning nanofactory, for now the greatest research attention is being concentrated on the first area: proving the feasibility, both theoretical and experimental, of achieving diamond mechanosynthesis

DMS is the positionally controlled fabrication of molecularly precise diamondoid structures. As an important part of this effort we have compiled the first comprehensive list of technical challenges -- both theoretical and experimental -- that currently stand in the way of achieving DMS.

We welcome suggestions for additions to this list, as well as offers of assistance from the nanoscience and nanoengineering communities to try to overcome these obstacles. It is also noteworthy that our collaborative efforts include a nascent experimental effort. The precursor to the Nanofactory Collaboration was informally initiated by myself and Ralph Merkle in late 2000 when we worked together at Zyvex. Our continuing efforts, and those of others, have now grown into direct collaborations among 23 researchers or other participants (including 16 Ph.D's or Ph.D candidates) at 10 organizations in 4 countries (U.S., U.K., Russia, and Belgium), as of 2006. Interested readers should visit the website for more details. We are also looking for funding to greatly expand and accelerate the effort.

Some medical treatments are quite costly, do you see nanotechnology changing the cost of medical care in the future?

The earliest treatments might be quite costly but this state of affairs should not last too long. Medical nanorobots need be no more expensive than any of today's medical technologies. Manufacturing costs using nanofactories can in principle be as low as \$1/kg (<http://www.rfreitas.com/Nano/NoninflationaryPN.pdf>). It is true that regulatory and design costs unique to nanorobots employed in medical applications might be several orders of magnitude more expensive than this. But even at \$1000/kg -- the price

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Ambitious Nanomedical Goals Enter the Mainstream

By Christine Peterson



“Visions of advanced nanomedicine, once regarded as highly speculative, have also entered mainstream medical research.”

Christine Peterson
Co-Founder and Vice President
Foresight Nanotech Institute

As the boomer generation advances in age, it becomes increasingly urgent to find ways to address the effects of disease and aging and reduce the number of years that older folks spend in expensive states of marginal health. Many boomers will make it past 100 — I hope to myself — but having watched relatives get that far, it’s clear that we need better ways to do it. How can seniors stay healthy enough to enjoy life and, ideally, continue to be financially self-supporting as long as possible,

relieving younger generations of the potentially crushing long-term care costs now on the horizon?

Near Term Nanomaterials for Medicine

Nanotechnology can help, even in today’s early “nanomaterials” stage of nanotech. Already we see frequent announcements of encouraging early research results for new drug delivery techniques, especially for cancer. Most of us have had a friend or relative go through the horrid surgery/radiation/chemotherapy process used today — sometimes it works, often it doesn’t. While more in the U.S. die of heart disease than cancer, the latter is more feared, in part due to these treatments.

Some of you have been around long enough to remember the War on Cancer announced by U.S. President Nixon in 1971. It didn’t work out too well, to the point that the phrase “war on cancer” got to have an ironic ring. Based on this it’s easy to understand why the National Cancer Institute tended to be more conservative in their goals once this state of affairs became clear.

But not anymore. Although I’d seen numerous strongly encouraging early research results announced for nanotech drug therapies for cancer, I was still surprised by the NCI’s aggressive and optimistic new goal: “eliminating suffering and death from cancer by 2015.” It’s not “cure cancer by 2015,” but it’s close.

Whether we reach that goal by 2015, or whether it takes a bit longer, the point is that NCI is feeling its oats. They’ve got their hopes up, and I have to admit that seeing the phrase “complete tumor elimination” show up in a nanotech-based drug trial in

(Continued on page 18)



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212-332-3443 David Keenan, President and Chief Executive Officer**

it provides society an opportunity to examine new options for solving old problems in all these important life science areas.

What do you anticipate as the greatest benefits of nanotechnology in the field of medicine, health and longevity?

I often give lectures to traditional medical professionals who are striving to understand how to integrate present nanomedicine concepts into their current and future practices. The common denominator of understanding in these groups is the fact that all protein, DNA/RNA and virus constructs are understood to be precise bio-structures with well defined nano dimensions. As such, there are good nano-structures (i.e., proteins and DNA/RNA) that support life/good health and bad nano-structures (i.e. viruses) that are usually associated with disease and reduced longevity. The role of our immune system is to engage our good nano structures (i.e., proteins such as IgG antibodies, etc.) in a defensive battle involving recognition groups and receptor sites to identify and destroy the bad nano-structures. The surface areas required for these recognition/receptor site events are measured in square nanometers (i.e., 6-10 sq. nm). Since the quality and efficiency of the human immune system largely defines our state of health and longevity, it behoves us to understand all the nano issues associated with the interaction of these good and bad nanostructures. Obviously these specific nano-parameters constitute a significant sector of that science we now recognize as "nanomedicine." This is just one example of the significant role that nanomedicine is expected to play in the field of human medicine, health and longevity.

Do you see any public or policy conflicts, such as equal access debates, resulting from increasing health and longevity through nanotechnology?

These issues have not formally emerged to any significant degree from my perspective. Perhaps it may be due to the fact that we are too early in the nanotechnology revolution to have demonstrated any "quantum jump" type nano-solutions to critical issues in the areas of health and longevity. However, I am certain that public policy organizations, the government (i.e., the FDA and EPA) and the public have considerable anticipation and apprehension that will materialize when the first major nano-based "breakthroughs" occur.

If you were in the office pool, which nanotech medical solution would you put your money on to make the biggest impact in the future?

I think that the Starpharma, dendrimer based microbicides (i.e., VivaGel) which are in clinical trials for HIV and genital herpes prevention will have the greatest impact on human health in the shortest time frame.

Dr. Tomalia launched his academic and entrepreneurial ventures after a 25-year management and senior scientist career with The Dow Chemical Company. During that time, he was credited with numerous commercial developments which included Citrucel® (now marketed by GlaxoSmithKline), cationic polymerization of 2-oxazolines and discovery of the fourth major class of macromolecular architecture; namely, "dendritic polymers." He is the inventor and originator of the term "dendrimers," and is listed on over 110 US patents and more than 200 peer reviewed publications. Dr. Tomalia serves as the president and CTO of DNT while he remains active in the academic community.



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of a good laptop computer today – a single basic nanorobotic treatment requiring 1 cc of devices would cost about \$1. Since diamondoid nanorobots are not biodegradable but are intended to be removed from the body after their job is done, they can be recycled which will help to hold down costs. The big unknown is the regulatory burden. This could be substantial -- bringing a new drug to market can cost \$500M or more today -- but will ultimately be amortized over a very large number of treatments administered worldwide.

What do you anticipate as the upsides of nanotechnology in the field of medicine, health and longevity?

The biggest upside is an extreme extension of the human health-span – that is, super longevity coupled with youthful healthy life up until the last moment. The leading causes of death by mid-century will probably be suicide, accidents, and homicides of various kinds. Heart disease, cancer and stroke -- today's leading killers in the developed world -- will be all but forgotten. Diseases involving natural pathogens will be quick and easy to treat.

Do you see nanotechnology increasing health and longevity resulting in any public or policy conflicts? Equal access issues?

Falling costs should eventually provide equal access. The main conflict will be between (a) the traditional institutions that emerged in the past to manage the scarcity of medical resources and the sequelae of short lifespans (e.g., fiscal planning based on the actuarial assumptions underlying the Social Security system where people are expected to die by age 80) and (b) the new institutions, as yet unborn, that will be required to accommodate the needs of a population of perpetually youthful and healthy mult centenarians. There will be inevitable conflicts as we transition from the former to the latter, but the transition will be worth the effort because enjoying longer healthier lives is a nearly universal human desire.

Reference websites:

<http://www.MolecularAssembler.com/Nanofactory/DMS.htm>
<http://www.MolecularAssembler.com/Nanofactory/Challenges.htm>

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Why Care About Nanotechnology?

By Teri Odom

Why care about nanotechnology?

Besides the technological prospects that nanotechnology offers (such as sensitive diagnostics, secure communications, and advanced nanocomposites), we should care about nanotechnology because it can excite even the most jaded student of science. We have creative license to think about how new discoveries in science and engineering can be combined in ways to address hard problems. We can test whether revolutionary advances have advantages over evolutionary progress. And perhaps most importantly, nanotechnology can make a mark on education. Because of its inherent multi-disciplinary nature, it can capture the imagination of the next generation of scientists and engineers -- it is a small hook that can net a very large catch.

Why is nanotechnology important for the general public to understand?

The promise of nanotechnology is not without its risks. If the public can somehow participate in the scientific discovery process, they can "buy into" the cost and outcome associated with translating nanoscience into a technology. As was evident in the biotechnology effort of genetically modified food, the public does not simply want to accept the fruits of a new technology -- they want to be part of the labor that is involved in bringing it to bear. If the public is educated about the science, they can make intelligent decisions regarding the technology, which can right incorrect perceptions (e.g., self-replicating nano-robots) but still raise relevant issues (e.g., privacy). And so education is paramount.

What are your research goals?

We are interested in the science of small structures. We use three distinct but complementary approaches to create nanostructures: top-down, bottom-up, and a combination of both approaches. That is, we combine the ease and control of fabrication with the functionality and crystallinity of chemical methods to produce the most scientifically interesting and technologically useful structures. We are most focused on the unique optical properties of nanostructures as their size, shape, and composition are changed. But we then want to know what happens when they are assembled or organized into well-ordered arrays; how do they interact with each other? These assembled structures often exhibit surprising "collective" properties -- which can serve as prototypes for understanding related problems at similar length scales, such as biological processes and systems.

How is your research relevant to the general public?

We have developed a simple and inexpensive set of large-area, nanoscale patterning tools that can reach into broad areas ranging from optical communication to electronic devices to biological assays. We not only use our tools to uncover new science but also exploit them to provide practical ways of assembling and fabricating nanoscale structures over macroscale areas. In one sense, part of what we do is to provide a first step in transitioning nanoscience into an emerging technology.



Teri Odom
Assistant Professor, Department of Chemistry
Northwestern University

"We should care about nanotechnology because it can excite even the most jaded student of science. We have creative license to think about how new discoveries in science and engineering can be combined in ways to address hard problems."

In context with your research, how do you see it impacting the future?

Because we believe that advances in science and tools are intertwined, our hope is that as the tools we've developed to create nanoscale structures are accessible to researchers in diverse fields, new ways of thinking about problems will result. Thus, scientific progress can be enabled at the interface of different disciplines and also proceed at a much faster pace than would have been possible otherwise.

International Technology Roadmap for Productive Nanosystems

The working group team of world-class scientists, engineers, business leaders and academics met in early-March 2006. Hosted by our partner, Battelle, at their Oak Ridge facility in Tennessee, the group is well on the way to developing a roadmap that will accelerate the development of molecular machines. The group met again in June at another Battelle facility, Brookhaven National Labs, in New York.

With another meeting planned for December 2006, the Roadmap committee is on schedule to release the Executive Summary of the Roadmap in Spring 2007. For information about sponsoring the Roadmap, contact Foresight Nanotech Institute at foresight@foresight.org

Current emphasis is on four pathways to atomically precise manufacturing. The Roadmap will also address the enabling technologies related to each pathway

Roadmap Pathways:

1. Self-directed manipulation
2. Machining (Feynman approach)
3. Bio Synthesomes
4. Chemistry and Materials Science

Definition of Productive Nanosystems:

Productive Nanosystems are functional systems that make atomically precise structures, components, and devices under programmable control.

Review: Top Nanotech Research

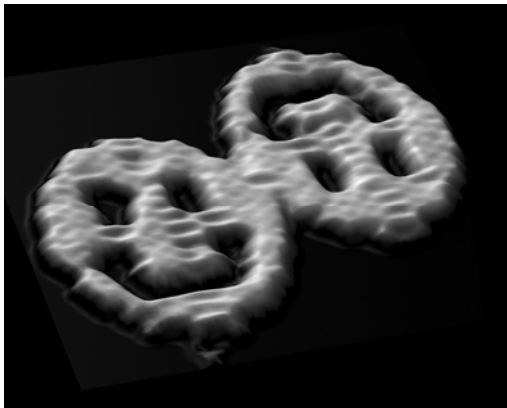
By James Lewis, PhD

Two-Dimensional DNA Nanostructures of Arbitrary Shape

Paul W.K. Rothemund, "Folding DNA to create nanoscale shapes and patterns", *Nature* 440, 297-302 (16 March 2006)

Paul Rothemund of Caltech—who, along with Erik Winfree won the 2006 Foresight Institute Feynman Prize in Nanotechnology (see page 14)—has developed a simple, inexpensive way to obtain a wide variety of two-dimensional DNA nanostructures, in high yields. Typically these DNA nanostructures are about 100 nm in diameter and 2 nm thick (the diameter of the DNA double helix). Based on the size and packing of the short DNA double helical segments used to form these structures, the resolution at which features can be designed is about 6 nm. Thus these DNA nanostructures can be viewed as about 200 pixels arranged in whatever pattern of surface shapes and holes is desired. Among the stunning atomic force microscope (AFM) images presented to document the nanostructures created are a "smiley face" and a low resolution map of the western hemisphere.

During the past 15 years DNA nanotechnology has achieved striking successes in creating two-dimensional arrays, three-dimensional structures, and simple nanomechanical devices from the programmed assembly of many short strands of DNA (typically, a few dozen nucleotides long). For technical reasons, however, complex structures were difficult to prepare and were obtained in low yields. In the process he terms 'scaffolded DNA origami' Rothemund also uses a set of small single-stranded DNA molecules to guide the folding of a long single-stranded DNA molecule, but his procedure is a simple 'one-pot' method and can be used to form arbitrary two-dimensional shapes. Each of the nanostructures Rothemund presents was formed by mixing a scaffold of about 7000 nucleotides with about 250 different 30-nucleotide-long DNA molecules, which he terms 'staple strands', specifically chosen to make the scaffold fold into the desired shape.



DNA Shape (two smiley shaped molecules)
Credit—Paul W.K. Rothemund and Nick Papadakis

A major advance occurred a couple years ago when William Shih and colleagues designed a long (1669 nucleotides) DNA molecule that folded in the presence of five 40 nucleotide-long DNA molecules into a regular octahedron of 22 nm diameter [William M. Shih, Joel D. Quispe & Gerald F. Joyce, "A 1.7-kilobase single-stranded DNA that folds into a nanoscale octahedron", *Nature* 427, 618-621 (12 February 2004)]. Unlike earlier products of DNA nanotechnology, this 1669-nucleotide single-stranded DNA

molecule could be amplified by polymerase enzymes, and thus could be cloned to produce the nanostructure in large amounts, and could be adapted to specific purposes through directed evolution. Because a large molecule was designed to fold into a desired shape, this approach has been referred to as 'DNA origami'. However, this approach has not been adapted to make other shapes.

The first step in designing scaffolded DNA origami is to outline the desired shape, and fill it with an even number of cylinders representing short segments of double helical DNA. To hold the helices together, an array of points is designated where a DNA strand would switch from one short helix to the adjacent one. The scaffold strand is then conceptualized as folding in a raster pattern to fill the outline such that it comprises one of the two strands in each helix. There are necessary constraints on the folding based on the geometry of double stranded DNA. The folding path and the sequence of the scaffold strand are entered into a computer program that then designs the set of staple strands. Strain energies are calculated. Staple sequences are optimized to minimize strain and maximize binding to the scaffold. The staple strands are synthesized and mixed with the scaffold strand, and the structures that form are then deposited on a mica surface for imaging with an AFM. For different shapes tested, the yield of well-formed structures seen with the AFM varied from about 10% to about 90%. In the case of the smiley face structures 70% were well-formed.

In general, these DNA nanostructures showed the target shape to within the expected 6-nm pixel resolution determined by the size of the DNA helix formed by each staple strand. The staple strands also allowed the optional decoration of each pixel with an additional structure to produce a binary pixel. A wide variety of DNA modifications are possible, but in the case Rothemund reports here, a dumbbell loop of DNA is inserted in the middle of the staple strand. Pixels formed with staple strands containing the insert show greater height above the mica surface because of the hairpin protruding above the double helix, and thus appear in the AFM as brighter than pixels without the insert in the staple strand. The map of the western hemisphere is composed of light continent pixels and dark ocean pixels. The images show occasional missing pixels, but it is not clear whether these are the results of imperfect assembly or of damage caused by AFM imaging. Specially designed staple strands could be used to join individual nanostructures into larger structures, for example, joining six triangles to form a hexagon.

Rothemund believes that scaffolded DNA origami can be extended to create larger and more complex structures, including three-dimensional structures, and as a substrate for arranging other types of molecules.

"An obvious application of patterned DNA origami would be the creation of a 'nanobreadboard', to which diverse components could be added. The attachment of proteins, for example, might allow novel biological experiments aimed at modeling complex protein assemblies and examining the effects of spatial organization, whereas molecular electronic or plasmonic circuits might be created by attaching nanowires, carbon nanotubes or gold nanoparticles."

(Continued on page 15)

Nanotechnology Applications and Markets

by Lawrence Gasman

Book Review by James Lewis, PhD



"I am going to take the position that the vast majority of what is today being characterized as nanotech really falls into three areas: nanoelectronics, nanobiotechnology, and nanoenergy."

Lawrence Gasman
President
NanoMarkets, LC

Lawrence Gasman has written a concise, non-technical overview of nanotechnology that may be the best guide available for evaluating near-term to intermediate-term business opportunities in nanotechnology. The intent of *Nanotechnology Applications and Markets* can be surmised from the author's dedication, which reads in part "To the victims of high-tech bubbles everywhere and everywhen". So that his readers can avoid becoming victims of a potential nanotechnology bubble, Gasman provides a framework for evaluating the business potential of nanotechnology that avoids both unrealistic expectations and irrational pessimism. This book is clearly about business opportunities and not about technology itself. The general approach is to work backwards from demand and markets to need, and opportunities for nanotechnology to meet those needs.

Gasman has 20 years of professional experience analyzing the commercial impact of new technology. Until a few years ago his work was analyzing telecommunications technology. He relates in his preface that since reading Eric Drexler's *Engines of Creation* twenty years ago, he has been thinking about the impact of nanotechnology and made that topic his professional focus three years ago.

Gasman's focus is, "broadly speaking, an emerging technology that enables engineers to design and build new materials and products at the molecular level." This definition of nanotechnology is much less ambitious and much more near-term than is molecular manufacturing, and is in line with the pervasive use of the term nanotechnology to encompass a diverse group of areas that have to do with engineering at a length scale of less than 100 nm.

While Gasman does not cover molecular manufacturing, his reason is not a lack of interest in the goal. "It is possible that we will never get to the stage that Drexler describes in his book, but it seems nearly certain that we will make it most of the way." Rather, it is outside the time frame of near-term business opportunities. The approach here is very hard-headed and practical: "If a nanotech boom occurs, it will be important for nanotech businesses not to be swayed by the hype and keep a firm grasp of market realities to build sustainable businesses." Also: "It will behoove emerging nanotech firms to focus on relatively easy-to-prove cost-related benefits than on the gee-whiz features of a revolutionary technology."

To evaluate those business opportunities, Gasman explores the role of nanotechnology as an enabling technology to allow firms to respond to the "megatrends" that will dominate the economy in the near future: mobile communications, energy, and biomedicine and pharmaceuticals.

A brief overview of nanoscience and nanotechnology leads into a consideration of the salient features of nanobusiness. One such feature is the exceptional importance of intellectual property (IP) in Nanotech: "at the present time it is hard to overestimate the importance that investors and the nanotech community places on IP" But Gasman is skeptical that IP will continue to get so much attention. Because of the diversity of nanotechnology platforms and materials, there may be many routes to achieve the same performance goal. For example, it may be possible to develop nanotech computer memories from thin-film magnetics, organic electronics, or carbon nanotubes.

Perhaps the most useful aspect of *Nanotechnology Applications and Markets* is the proposal, argued very convincingly in this reviewer's opinion, that the coming impact of nanotechnology on the economy can be largely understood by focusing on three sectors. "I am going to take the position that the vast majority of what is today being characterized as nanotech really falls into three areas: nanoelectronics, nanobiotechnology, and nanoenergy. Nanoelectronics encompasses both electronics and semiconductor industries. What I am calling nanobiotechnology includes medicine, healthcare, pharmaceuticals, and life sciences more generally. The nanoenergy sector that I have in mind covers fossil fuels, alternative energy sources, and energy sources for mobile electronics." The effects of nanotechnology will be felt throughout the economy, but mainly through the effects on these three sectors. One chapter is devoted to the near-term nanotechnology-enabled business opportunities in each of these three sectors. In each case Gasman begins with the challenges facing the sector, and then proceeds to identify the specific ways in which nanotech could create opportunities.

For the nanoelectronics sector, the central observation is that the semiconductor, computing, and communications industries are approaching fundamental limits to extending Moore's Law using conventional tools and materials. "The problems that the industry is experiencing as it tries to push Moore's Law further are fourfold: too much heat, a lack of high-volume manufacturing methods, a materials crisis, and quantum/atomic level statistical fluctuations." However, near-term solutions to these problems are constrained by a very practical consideration: "any nanotechnology solution that isn't designed to work in close harmony with existing CMOS infrastructure has no chance of commercial success." Nanotechnology solutions independent of CMOS infrastructure will probably not be built for another decade. Therefore complete processors built from carbon nanotubes (CNT) are at least 10 years away, but within next 5 years CNTs will find commercial use in sensors, flat panel displays, memories, interconnects, and heat sinks, and perhaps in semiconductor manufacturing through forming arrays of e-beam generators for e-beam lithography. Gasman's firm predicts that "the entire nanotube electronics market will be worth \$6.4 billion by 2010, with most of those revenues coming from memory, sensors, and displays." The potential

(Continued on page 17)

Foresight Nanotech Institute 2006 Prizes



*Dr. Paul W.K. Rothemund
Feynman Prize Winner*



*Dr. Erik Winfree
Feynman Prize Winner*

Foresight Nanotech Institute was pleased to award our prizes this year to individuals whose work in research, communication and study are moving our society towards the ultimate goal of atomically-precise manufacturing.

Feynman Prize Winners

Molecular nanotechnology, for many years, was simply a vision and a theory. This research of this year's Feynman prize-winners, Drs. Erik Winfree and Paul W.K. Rothemund of Caltech, is an example of the rapid advances being made in this science. For the first time ever, the same research team is being honored the prizes in both categories, theory and experimental. This is an exciting example of how nanotechnology theory and experiment are meeting in research institutions. Soon the discoveries that used to only be a vision will become a reality.

Drs. Erik Winfree and Paul W.K. Rothemund received the Feynman prizes for their pioneering research in the production of ever more complicated two-dimensional arrays of nanosystems, perhaps leading eventually to the construction of atomically-precise products through the use of molecular machine systems.

Dr. Paul Rothemund

Dr. Paul W.K. Rothemund is a graduate of Caltech, where he dual majored in biology and computer science. His undergraduate project in information theory was one of the first designs for a DNA computer, and became one of the first patents for DNA computation. He has a long-standing interest in problems at the interface of biology, chemistry, and computer science: he seeks to understand what parts of biology may be best viewed as computation. He is also working to turn the process of chemical synthesis into an exercise in programming. After receiving his Ph.D. at the University of Southern California, he was awarded a Beckman postdoctoral fellowship and returned to Caltech to work with fellow Feynman Prize recipient, Erik Winfree, on algorithmic self-assembly of DNA. Dr. Rothemund is currently a research fellow in Caltech's Center for the Physics of Information.

Dr. Erik Winfree

Dr. Erik Winfree is an Associate Professor in Computer Science and Computation and Neural Systems at Caltech. He received a Bachelor of Science in mathematics and computer science from the University of Chicago, and a Ph.D. in computation and neural systems from Caltech. His research concerns the theory and engineering of autonomous biochemical algorithms using in vitro systems of DNA and enzymes, including programmable DNA self-assembly, DNA and RNA conformational switches and devices, and RNA transcriptional circuits. Prior to joining the faculty at Caltech in 1999, Dr. Winfree was a Lewis Thomas Postdoctoral Fellow in Molecular Biology at Princeton, and a Visiting Scientist at the MIT AI Lab.

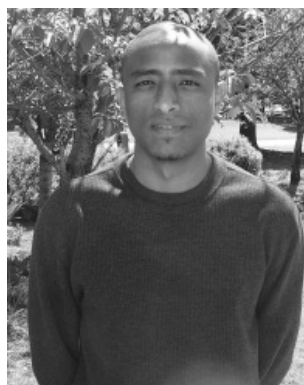


*J. Storrs Hall
Communication Prize Winner*

Foresight Institute Prize in Communication

The Foresight Institute Prize in Communication was awarded to J. Storrs Hall, Ph.D., an independent scientist and author, for his recently published book "Nanofuture: What's Next For Nanotechnology." He is currently writing another book about artificial intelligence and machine ethics. Dr. Hall was the founding Chief Scientist of Nanorex Inc, and is regarded as one of the most significant thinkers in

the field of molecular nanotechnology. He founded the sci.nanotech Usenet newsgroup and moderated it for ten years. He holds a Ph.D. in Computer Science from Rutgers University. His research emphasis was on artificial intelligence, compilers, microprocessor design, massively parallel processor design, CAD software, and automated multi-level design.



*Berhane Temelso
Distinguished Student*

Foresight Institute Distinguished Student Award

Berhane Temelso, a graduate student in the School of Chemistry and Biochemistry, Georgia Institute of Technology, was awarded the Foresight Institute Distinguished Student Award for his work on "High-Level ab Initio Studies of Hydrogen Abstraction in Prototype Mechanosynthesis Systems." Temelso, earned a Bachelor of Science in physics from Berea College, where he won the

Waldemar Noll Award in Physics. He is currently in the PhD program in the School of Chemistry and Biochemistry at the Georgia Institute of Technology. He recently won a Cherry Emerson Graduate Fellowship and a poster award at the Sanibel Symposium on Quantum Chemistry and Biology.

Coupled Mechanical Motion in a Molecular Machine

Takahiro Muraoka, Kazushi Kinbara & Takuzo Aida
"Mechanical twisting of a guest by a photoresponsive host"
Nature **440**, 512-515 (23 March 2006).

Chemists at the University of Tokyo announced a substantial step forward in the development of molecular machine systems. They designed a molecular system in which mechanical movement in one molecule is transmitted in a controlled and reversible manner to a second molecule, something which had not been accomplished in the various molecular devices, such as shuttles, brakes, unidirectional rotors and tweezers, created to date. "Here we show that light-induced scissor-like conformational changes of one molecule can give rise to mechanical twisting of a non-covalently bound guest molecule." This advance is based upon their previous work on a molecular scissors: Takahiro Muraoka, Kazushi Kinbara, Yuka Kobayashi, and Takuzo Aida "Light-Driven Open-Close Motion of Chiral Molecular Scissors", *J. Am. Chem. Soc.* **125**, 5612-5613 (14 May 2003).

In this earlier work they constructed a molecule such that one part of the molecule undergoes a change in conformation (shape) in response to illumination with ultraviolet (UV) or visible light, and that change causes an open-close motion of the scissors blades moieties (parts of the molecule). It is a molecule of joined parts in which movement in one part causes movement in the interlocked parts. In the molecular scissors they designed and synthesized the blade moieties are composed of two phenyl groups, the pivot is a tetrasubstituted ferrocene, the handle parts are two phenylene groups, which are connected by an azobenzene unit through ethylene linkages. The junction of the handles to the pivot destroys the optical symmetry of the joined moieties and thus renders the larger part optically active, which means that the angular motion of the pivotal ferrocene unit can be evaluated by means of circular dichroism (CD) spectroscopy. Ferrocene consists of two cyclopentadienyl rings bound parallel to each other, on opposite sides of a central iron (II) atom, and able to rotate freely with respect to each other.

Photoillumination (switching between UV and visible light) causes isomerization around the central double bond of the azobene. In the *trans* configuration the connections to the handles are on opposite sides of the double bond, forcing the handles apart and the thus the blades together; in the *cis* configuration the connections to the handles are on the same side of the double bond, bringing the handles together and thus forcing the blades apart. The authors' quantum mechanical calculations indicated that in the *trans* configuration the angle between the blades would be 9.2 degrees, while in *cis* it would be 58.2 degrees. UV drives the transition *trans* to *cis* and visible light *cis* to *trans*. CD spectroscopy confirmed that photoisomerization caused the ferrocene rings to rotate with respect to each other. Confirmation was seen with nuclear magnetic resonance spectroscopy.

For their current advance, the simple phenyl group blades of the earlier scissors were extended with zinc porphyrin units to provide binding sites so the scissors could function as a "host" for a "guest" molecule. Zinc porphyrin is known to form a coordination complex with nitrogenous bases (called "ligands"). The guest compound here is a "bidentate" ligand called 4,4'-biisoquinoline. This molecule

contains two nitrogenous bases (isoquinolines, which are naphthalenes in which a nitrogen replaces the carbon atom in position 2) connected at their 4 positions with a single bond so that they can twist around this bond. Therefore, as the blades of the scissors open and close the two halves of the guest molecule will twist around the bond joining the two halves. Spectroscopy showed that the host bound strongly to the guest, as expected.

When the guest is free in solution, it is not optically active, but when it is bound to the host it is twisted into a nonplanar configuration, which renders it optically active. It thus contributes to the CD spectrum of the molecule. Upon irradiation with UV to induce *trans* to *cis* isomerization of the azobenzene, opening the scissors blades, the guest is twisted into a more planar conformation, and the CD spectrum decreased, as expected. The reverse change in the CD was seen upon irradiation with visible light to induce the backward isomerization.

The authors have thus demonstrated the intermolecular coupling of mechanical motion. They speculate that this accomplishment "might allow for the remote control of molecular events in larger interlocked molecular systems." Such a capability could greatly facilitate the development of productive nanosystems.

**Nanotechnology is coming
and it will have a tremendous
impact on our society.**

**What's your priority for
nanotechnology: cancer
treatments, sustainable energy,
clean water, a restored
environment, space
development, or new
manufacturing capabilities?**

**Would you like to help
influence the direction
of this powerful technology?**

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My Summer with Foresight

By Jacob Heller



Jacob Heller
Public Policy Intern
Summer 2006

As a Silicon Valley native interested in politics and economics, I have always felt that the connection between technology, policy, and economics is both obvious and important. Sure, we can create amazing technologies, but that doesn't guarantee they will be put to their best use. It is becoming clear that nanotechnology will become one of the most important technological revolutions in human history, so it is imperative that we begin discussing which public policies will maximize nanotech's benefits, while minimizing its downsides.

It was clear that the Foresight Nanotech Institute was the leading public policy think tank that addressed these issues, and I wanted to be a part of it. So, I volunteered a summer to research nanotech policy with Foresight. Working with Foresight turned out better than I could have ever imagined, and it has been one of the most educational and intellectually invigorating experiences of my college career. I have had direct access to leaders in nanotech policy, most importantly Christine Peterson, and the opportunity to independently research nanotech policy issues.

The product of my labor was policy issue briefs for Foresight's website (<http://www.foresight.org/policy>), and a full-length book chapter co-authored with Christine about the potential benefits of nanotech, based on Foresight's Nanotech Challenges,

Jacob Heller is a Politics and Economics double-major at Pitzer College. He founded A Computer in Every Home, an organization that provides computers to needy students. Jacob is the director of Technology Policy at the Roosevelt Institution, debates nationally and internationally, and campaigns for the Democratic Party. He was the 2004 Economic Vitality and Energy Coordinator at the Silicon Valley Leadership Group. He is an editor for a website devoted to digital content creation, and has published over 120 articles on digital media.

as well as the political obstacles to maximizing those benefits.

I also began a review of patent policy as it pertains to nanotech, a project that proved so large that I will continue to research it well into the school year, and the result will likely become my senior thesis.

The ability to work with Foresight, to investigate such cutting edge topics, and to publish as an undergraduate will undoubtedly help me later in life. However, the most important things I will take away from Foresight are the experience and knowledge gained working here. I came in to Foresight with nothing more than an interest in technology policy and a cursory knowledge of nanotech. After spending months reading articles and books, talking with industry and policy luminaries, and devoting substantial thought to these subjects, I now feel prepared to seriously take on both issues. Although graduate school and some other endeavors are next on the list, after my positive experience at Foresight I can definitely see myself entering the world of technology policy as a career later in life.

Though I was a volunteer intern, I know that I have been benefited in ways that money cannot buy. The chance to work on policy issues that are vitally important with the friendly staff at Foresight was superb. After a summer researching nanotech policy and working with Foresight, it is clear to me that Foresight's mission of producing sound public policy that maximizes the benefits of nanotech is essential. I look forward to working with them to help achieve this important goal in the future. *Thank You, Foresight!*



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opportunities in the nanoelectronics sector afforded by developments in nanowires, spintronics, molecular electronics, plastic electronics, quantum dots, and nanophotonics are similarly explored. "Summarizing, the semiconductor and electronics industry seems to be where complex nano-enabled products will first create large new revenue opportunities."

The chapter exploring the nanoenergy sector illustrates how beginning the analysis with market needs rather than with technological possibilities often reveals unexpected opportunities. Most observers at least somewhat familiar with the capabilities of near-term nanotechnology, when considering applications in the energy sector, probably immediately think of the potential of nanostructures to increase the role of solar energy by providing inexpensive photovoltaics. Gasman discusses a wider range of opportunities. "This means that a lot more is involved than just energy generation, energy must be changed into different forms, stored until needed and then transported efficiently." In fact, he analyzes five areas of impact: the nano-enhanced fossil fuel sector, fuel cells and the nanoengineered hydrogen economy, nanosolar power, a nano-enhanced electricity grid, and nanopower for the pervasive communications network. Of these five areas, he believes the most immediate opportunities for nanotechnology lie in reducing the cost of power provided by fossil fuels. Specifically, he points to nanoparticles as sources of improved catalysts for more efficient use of fossil fuels. In terms of the market need for nanopower for the pervasive communications network, nano-enabled photovoltaics and fuel cells might be more than a few years away, but improving the performance of lithium ion batteries by replacing a conventional carbon anode with nanomaterials that provide a bigger surface area might present a near-term business opportunity.

The chapter on nanobiotechnology examines not only the nanotech business opportunities, but also the attitudes toward nanotechnology of those in medicine and the pharmaceutical industry. "Perhaps the main reason why nanomedicine has not yet garnered much respect in either healthcare practice or the healthcare/pharma industry is that it appears to be a long way off and therefore will seem to many an area that is not worth more than a few casual thoughts at this point in time."

Although Gasman is primarily interested in near-term and intermediate-term nanotechnology, he does not dismiss the long-term potential of nanotechnology in medicine. "I believe that nanomedicine will be where the biggest opportunities for nanotechnology will be found a decade from now. The potential for increased longevity that nanotechnology seems to present to us, coupled with the aging population seems to be an irresistible force, always assuming that nanomedicine can live up to its potential."

To give some indication of how broadly nanotechnology could affect the economy in the near future, Gasman devotes a chapter to exploring how products created in the nanoelectronics, nanobiotechnology, or nanoenergy sectors could also impact other industries. For example, nanosensors developed in the nanoelectronics sector could impact the food and agriculture segment of the economy.

The final chapter presents a six-step program for conducting a nanotechnology impact analysis to determine realistically how

nanotechnology could impact revenues and costs of a specific firm.

Nanotechnology Applications and Markets offers a balanced and reasoned framework for charting the near-term and mid-term business opportunities in nanotechnology, presented clearly and logically by an experienced observer. There is no attempt to comprehensively survey the impact of nanotechnology on business over the next five to ten years, but rather Gasman provides a map of what are likely to be the most important features, and a methodology to assist the reader in navigating the nanotechnology business landscape. To aid understanding, each chapter ends with "Summary: Key Takeaways from This Chapter" and "Further Reading" sections. Throughout the narrative he makes explicit what factors he is considering and how he comes to his conclusions. Finally, from the nanotechnology overview to the six-step nanotechnology impact audit, the orientation of the book is to the practical needs of businesspeople who need to understand the impact of nanotechnology.

Lawrence Gasman is principal analyst and founder of NanoMarkets LC, in Charlottesville, Virginia. He has over 25 years of experience as a high-tech consultant for companies including Analog Devices, Cisco, Hewlett-Packard, IBM, Intel, Fujitsu, NEC, Nortel and NTT, and is the author of three other books on telecommunications topics. He is also on the editorial board of the Foresight Nanotech Institute and is a regular contributor to the Nanotechweb.org.

Medical Experts - Mansoor Amiji
(Continued from page 6)

How do you see your current research impacting nanotechnology and medicine in the future?

I see our work on nanotechnology-based delivery systems to allow for the development of drugs that had poor properties and could not be formulated, these systems will overcome biological barriers to delivery of drugs and genes so that many therapies could be realized in the clinic, and allow for strategic therapeutic approaches with less toxicity to the patient.

Mansoor M. Amiji is an Associate Professor in the Department of Pharmaceutical Sciences, School of Pharmacy, Bouve College of Health Sciences at Northeastern University in Boston, Massachusetts.

Dr. Amiji received his undergraduate degree in pharmacy (magna cum laude) from Northeastern University in the 1988 and a doctoral degree in pharmaceuticals from Purdue University, West Lafayette, IN in the summer of 1992. Dr. Amiji returned to Northeastern University as an Assistant Professor in January of 1993. He received tenure and was promoted to Associate Professor in 1999. During a sabbatical leave in 2000, Dr. Amiji worked at the Massachusetts Institute of Technology in Professor Robert Langer's lab.

*Dr. Amiji's research focuses on polymeric technologies for delivery of drugs and genes to specific target sites in the body, nanotechnology for medical diagnosis and therapy, and development of biocompatible materials. He has published over 70 peer-reviewed publications, eight book chapters, and is an author of the books *Applied Physical Pharmacy* (McGraw-Hill, 2002) and *iPolymeric Gene Delivery: Principles and Applications I* (CRC Press, 2004).*

Ambitious Nanomedical Goals

Ambitious Nanomedical Goals Enter the Mainstream
(Continued from page 8)

animals did the same for me. Remember, sometimes there truly are major medical breakthroughs that make a huge difference for a lot of people: getting doctors to wash their hands was a big one, and so was the discovery of penicillin. Nanomaterials-based cancer detection and treatment may well be another. Even for those of us who focus on more advanced nanodevices and systems, this application of today's relatively crude nanomaterials should be truly exciting—you and your loved ones may avoid a lot of pain thanks to this work. Let's make sure the funding for this keeps flowing, and increases.

Longer Term Nanomedicine: Devices and Systems

While you sometimes see today's nanomaterials-based drug delivery work referred to as "devices" and "systems," the structures involved are still relatively simple—the parts do not move with respect to each other, nor is electric current flow used as in electronics. But these functions will come, with time. The ultimate goal is clear: We want to combine the molecular-scale chemical action of drugs with the three-dimensional physical rearrangement ability of surgery.

We have a long, long way to go to reach such an ambitious goal, but the pressure of increasing miniaturization makes the direction of progress clear. Professor Metin Sitti at Carnegie Mellon sketches some of the challenges on his "Micro Swimming Robots for medical applications" webpage: "Miniature, safe and energy efficient propulsion systems hold the key to maturing this technology but they pose significant challenges.

Scaling the macroscale swimming mechanisms to micro/nano length scales is unfeasible." They are, however, pressing on, as shown in the name of their group: the NanoRobotics Lab.

Sitti is also Chair of the IEEE Nanotechnology Council's Technical Committee on Nanorobotics and Nanomanufacturing, which includes these interest areas:

- Medical nanorobots
- Bio-nanomanipulation
- Biomimetic nanoscale structures, sensors, actuators, and mechanisms
- Directed self-assembly based nanomanufacturing
- Integration of self-assembly and precision assembly
- Nano- and molecular scale device and circuit manufacturing
- Massive nanomanufacturing
- Advanced human-machine interfaces for nanorobots


Visions of advanced nanomedicine, once regarded as highly speculative, have also entered mainstream medical research. Check out the U.S. National Institutes of Health "NIH Roadmap for Medical Research: Nanomedicine":

What if doctors could search out and destroy the very first cancer cells that would otherwise have caused a tumor to develop in the body? What if a broken part of a cell could be removed and replaced with a miniature biological machine? What if pumps the size of molecules could be implanted to deliver life-saving medicines precisely when and where they are needed? These scenarios may sound unbelievable, but they are the long-term goals of the NIH

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The Waitt Institute for Scientific Breakthroughs is committed to finding innovative ways to achieve the scientific discoveries that will change our world.

Our partnership with the Foresight Nanotech Institute will facilitate the cooperation and problem solving that has the potential to dramatically accelerate progress in this field.

Ambitious Nanomedical Goals

Ambitious Nanomedical Goals Enter the Mainstream
(Continued from page 18)

Roadmap's Nanomedicine initiative that we anticipate will yield medical benefits as early as 10 years from now.

And this is from NIH — not regarded as one of the more radical federal agencies. The term “nanomachine” shows up 162 times on their site, according to Google. (If you check this, enjoy the ad on the right: “Nanomachine: Whatever you’re looking for you can get it on eBay.” Wouldn’t that be nice—it certainly would save a lot of R&D time!)

The NIH Nanomedicine page continues:

Research conducted over the first few years will be directed toward gathering extensive information about the physical properties of intracellular structures that will inform us about how biology's molecular machines are built.

As this catalogue of the interactions between molecules and larger structures develops, patterns will emerge, and we will have a greater understanding of the intricate operations of molecular structures, processes, and networks inside living cells. Mapping these networks and understanding how they change over time is crucial to help us understand nature's rules of biological design that, in turn, will enable researchers to use this information to correct biological defects in unhealthy cells. This knowledge will lead to the development of new tools that will work at the "nano" scale and allow scientists to build synthetic biological devices, such as tiny sensors to scan for the presence of infectious agents or metabolic imbalances that could spell trouble for the body, and miniature devices to destroy the infectious agents or fix the "broken" parts in the cells. This initiative is an important component of the NIH Roadmap endeavor because these tools will be developed and applied, not just for a single disease or particular type of cell, but for a wide range of tissues and diseases.

Here at the end we can spot an understatement: “a wide range of tissues and diseases.” Gaining a molecular-scale understanding of how the body works will — eventually — lead to tools not just for a wide range of tissues and diseases, but for all of them. Every tissue, every disease, every “biological defect in unhealthy cells.” And when these repairs have been made, patients will be healthy: completely 100% physically healthy, period.

The question that naturally arises is, what about aging? Could an advanced level of nanomedicine stop or even reverse the aging process? It’s hard to see why not; aging is a physical process occurring at the molecular level. Gain real control at that level, and the process should be accessible to alteration. There are at least seven damage categories to the aging process which would require attention. A general ability to carry out molecular-level operations would provide the tools to study and then correct whatever damage mechanisms exist.

This brings us back to the challenge of the baby boomers aging mentioned above. The problem they are causing is not due to an extended lifespan, but an extended *unhealthy* lifespan. After retirement, we live for decades in increasingly poor health, consuming expensive high-tech medical care that doesn’t fully cure our ills.

It’s hard for us today to imagine a different situation, one in which effective medical care enables older people to feel —and look — just as healthy as younger ones. To most people, it seems impossible, ever, for this happen. But aging is just a (mind-bogglingly complex) physical process, presumably accessible to study, like other physical processes. After we develop the right tools, it will happen at some point. The interesting questions are when and where. And specifically, will it happen in time for you, the reader, to benefit?

Not everyone is pleased at the prospect of an end to human aging. The goal, although probably decades off, is already being debated by ethicists. These can be fun debates, but those in opposition to aging research have a tough job. Except perhaps for the human drive for reproduction, our drive to stay alive and healthy is perhaps the strongest one we have. It’s hard to see how that could be stopped. The best research could, however, move to Asia: when an anti-aging medicine conference was held in Singapore, it received support from faculty representing various scientific departments at the National University of Singapore, the Agency for Science, Technology and Research (A*STAR), the Singapore Economic Development Board, and the National Neuroscience Institute. Readers in favor of longevity will be pleased to know that English is one of the four official languages of Singapore; this will be handy when you travel there for treatments.

Of course, real longevity raises the issue of overpopulation. It turns out that the numbers depend more heavily on the birth rate than the death rate, and currently it looks as though it’s hard to keep a wealthy country from declining in population without immigration. Also, the level of technology that would enable longer lives would also enable us to live more lightly on the Earth, and to expand the biosphere beyond Earth. We shouldn’t have all our eggs in one basket anyway—look what happened to the dinosaurs. Space settlement would be good insurance.

Working Toward the Goal

These are heady thoughts to inspire us as we slog our way through the long, often tedious nanomaterials-nanodevices-nanosystems R&D process, working our way toward molecular-scale control of biological processes. We know of no more complex object than the human body, and it can go wrong in so many, many ways. But the difficulty of the challenge just makes it more attractive to our more ambitious researchers of molecular nanosystems.

It will take two kinds of work to reach these goals: (1) theory/design/modeling and (2) physical experimentation. That’s why we award two Foresight Institute Feynman Prizes every year, one in each category—we need both. This message was reinforced by the recent report from the National Academies titled “A Matter of Size: Triennial Review of the National Nanotechnology Initiative.” In examining progress toward the goal of atomically-precise manufacturing, they noted the “visionary engineering analysis” already done, and called for experimental testing to be coordinated with that theoretical modeling work.

Hear, hear. Let’s do just that, and keep both sets of researchers well-funded. With time and hard work, we’ll gain the ability to truly heal what ails us.

Become a Member

Twenty years ago Foresight and our supporters had the vision and the belief that nanotechnology could be a powerful force to improve the health and well-being of people and the planet. Today, nanotechnology is no longer just an idea, it is a fundamental force that is reaping rewards for humanity in fields ranging from biotech to energy, and with Foresight helping to lead the way, we are on the pathway to developing productive nanosystems — molecular machine systems that build with atomic precision.

This vision is now becoming reality.

Since our earliest days, Foresight has been promoting an understanding of the beneficial uses of nanotechnology. Foresight was the first voice and today remains the leading public interest voice for nanotechnology. We hold technical conferences and numerous member gatherings to enhance understanding and create opportunities for like-minded individuals to share ideas and establish relationships. Today Foresight is even more active and we hope you will become to be a member of our team.

Over the last year Foresight has achieved important work, which wouldn't have been possible without our member support:

- **Foresight and Battelle launched an International Technology Roadmap for Productive Nanosystems.** With initial funding from the Waitt Family Foundation supporting a team of world-class scientists, engineers, business leaders and academics, we are on our way to developing a roadmap that will accelerate the development of molecular machines.
- **Improved our web site**, where you can find even more information about nanotechnology, including a resource library that includes links and information about education, and jobs, and our popular blog Nanodot
- **Launched our weekly News Digest**, which provides the latest developments on nanotechnology and is read by 15,000 people in more than 125 countries each week.

We have updated our membership levels and benefits. These benefits provide exceptional value and recognize the important contribution our members make. With your help, we can continue to advance the field of nanotechnology.

We thank you for supporting the beneficial implementation of nanotechnology through Foresight. Please contact us any time with your requests, questions, and ideas for how Foresight can better further your goals for nanotechnology.

Foresight Nanotech Institute

The Foresight Update is a quarterly-publication for Foresight's participating and basic members. Foresight is a member-driven organization and we thank you for your support.

We hope you enjoy this issue. Our next publication will be devoted to Foresight Nanotechnology Challenge #4: Healing and Preserving the Environment.

Foresight Nanotech Institute would especially like to thank those who contributed to this issue on Nanotechnology and Health.

Foresight Nanotech Update

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Letter and opinion pieces will also be considered; submissions may be edited.

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