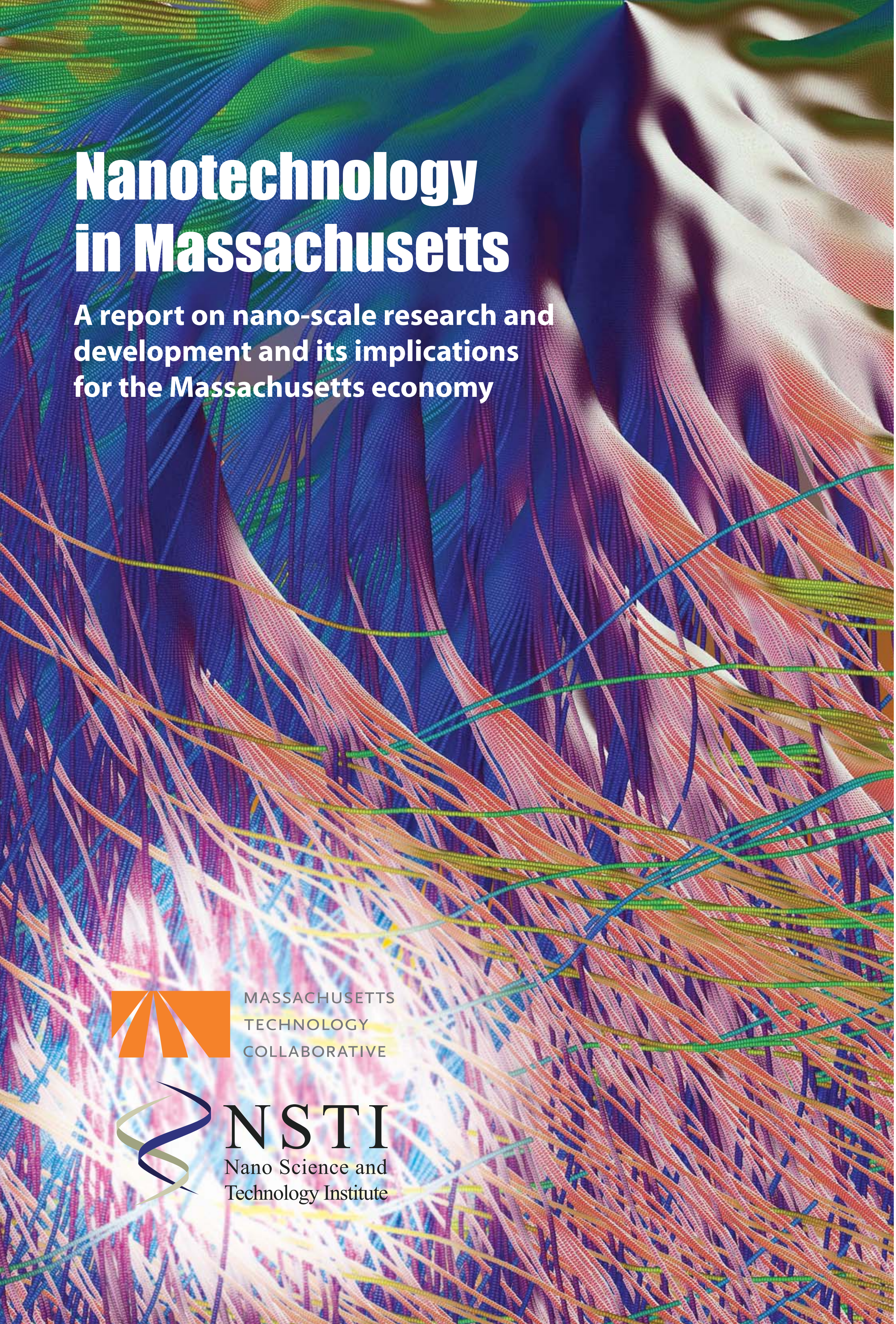

Nanotechnology in Massachusetts

A report on nano-scale research and development and its implications for the Massachusetts economy

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

NSTI
Nano Science and Technology Institute

The Massachusetts Innovation Outlook Series

Prepared by the Massachusetts Technology Collaborative and
the Nano Science and Technology Institute

About the Massachusetts Technology Collaborative (MTC):
The Massachusetts Technology Collaborative is the state's development agency for renewable energy and the innovation economy, which is responsible for one-quarter of all jobs in the state. MTC works with cutting-edge companies to create new jobs and stimulate economic activity in communities throughout the Commonwealth.

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About the Nano Science and Technology Institute (NSTI):
The Nano Science & Technology Institute is an interdisciplinary consultancy chartered with the promotion and integration of small technologies through education, technology and business development. NSTI provides technical and informational services to industrial and governmental organizations worldwide. NSTI is the founder and sponsor of the world's most comprehensive small technology scientific and business event, the annual Nanotechnology Conference and Trade Show (Nanotech). NSTI was founded in 1997 and is headquartered in Cambridge, Massachusetts.

www.nsti.org

NSTI
Nano Science and Technology Institute

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Cover Artwork provided by Professor Eric J. Heller, Harvard University
www-heller.harvard.edu
Two-dimensional electron flow in a semiconductor heterostructure. Electrons were launched from the upper center into a weakly random potential, the randomness caused by positively charged donor atoms in the "delta layer" above the 2 dimensional electron gas. Trajectories were launched evenly over 180 degrees, using strict overwrite of successive trajectories. This gives a three dimensional hidden surface effect to the caustics (cusps) which has much the same topology as an erosion landscape. Color is assigned according to the direction of the trajectory.

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MITT ROMNEY
GOVERNOR

KERRY HEALEY
LIEUTENANT GOVERNOR

Dear Reader:

It is with great pleasure that I introduce you to *Nanotechnology in Massachusetts*, a report from the Massachusetts Technology Collaborative and the Nano Science & Technology Institute.

Nanotechnology is rapidly becoming a significant national priority and an important target for new business development in Massachusetts. In the last three years, three Massachusetts institutions (MIT, the University of Massachusetts Amherst, and Harvard) have consistently ranked among the top half dozen institutions winning support from the National Nanotechnology Initiative. Virtually all of our state's research institutions have launched ambitious programs in nano-scale research. We expect that Massachusetts will continue to be a leader among states in attracting research funds now that Congress and President Bush have enacted the Nanotechnology Research and Development Act, legislation that will invest $3.7 billion in research over the next four years.

Massachusetts-based researchers are responsible for some of the most important research breakthroughs in nanotechnology thus far. As a result, nano-scale research is sparking the birth of a new generation of entrepreneurial firms in Massachusetts. Just as important, our existing technology firms have much to gain by absorbing new nano-scale innovations and establishing a clear leadership position in the international competition to create nanotechnology-related products and services.

Massachusetts is at the cutting edge of this exciting field. I invite you to read this report and to work with us in the months and years ahead as the nanotechnology revolution unfolds.

Sincerely,

Mitt Romney

Summary

The rapid advancements of nano-scale technologies are producing an explosive global increase in both research, and associated technology commercialization directed to impact most every existing industrial sector. An international competition has emerged in which regions, states and entire countries vie for competitive advantage in the attraction, development and retention of these emerging technology related firms and the jobs they will create. The U.S. government has demonstrated its commitment to these technologies through the recent four-year authorization of $3.7 billion in nanotechnology research and development. Massachusetts has emerged as one of the world's leading sources for new nano-scale technologies. Whether Massachusetts will emerge as a leader in commercialization of nanotechnologies is yet to be determined, and is dependent upon the many factors discussed herein.

The U.S. government's nanotechnology program, the National Nanotechnology Initiative (NNI), defines nanotechnology as:

A. A technology that operates at the atomic, molecular or macromolecular levels, in a length scale of 1-100 nanometers—in other words, technologies that are simply very small, —'nano small'—smaller than the 'micro' technologies in familiar use today.

B. A technology that creates or uses structures, devices and systems that have novel properties and functions because they harness forces that are only evident at level of atoms and molecules (the nanoscale)—in other words, technologies that are useful because of properties or capabilities that only a nanoscale device could offer.

C. Technologies that control or manipulate matter at the atomic scale—technologies that are capable of manipulating atoms and molecules by design.

The NNI definition of nanotechnology defines an area of research that is largely new and unexplored, so that the federal government's research spending can be prioritized accordingly. One can think of three distinct but overlapping circles—Circle A, Circle B, and Circle C. The NNI's target is the research that falls into the area where the three circles overlap.

Nanotechnology: Overlapping Clusters of Research and Industry

The NNI definition of nanotechnology is useful for NNI's purposes, but to assess the likely impact of nanotechnology on the Massachusetts economy it is wise to take a broader view. Nanoscale technologies will be adopted through integration with a wide variety of existing technologies, no matter how disruptive and potentially revolutionary they may prove to be. New nanoscale semiconductor devices may prove highly disruptive because they offer extreme miniaturization (see A, above), but they will most likely come to market through integration or linkage with technologies at work in the existing semiconductor industry and related industries.

New nanomaterials may prove disruptive because of the novel properties they will bring to a wide variety of products-extreme strength, and 'functionalization' that builds complex operations into devices at the molecular level. However, the nanomaterials most likely to be integrated into products are those that can be linked to materials and production technologies either at work today, or in development today within the materials industries.

Thus, while nanotechnology may be defined as the intersection of Circles A, B and C, all three circles should be seen as a cluster of technologies that will make nanotechnologies viable, and a source of real economic growth. This report provides an overview of those industries most likely to have a stake in nanoscale research and development—the industries that may well represent a 'cluster of clusters' that will be critical to the growth of a nanotechnology-related business sector in the future.

The utopian view of nanotechnology is that it will provide a platform of technical advancements that positively impact economy, workforce, existing industries and society in general. The U.S. federal government clearly believe in these possibilities, and demonstrated its belief in December 2003 when Congress and the President approved a four-year authorization of nearly $4 billion for the National Nanotechnology Initiative, thus making nanoscale research one of the few new spending priorities in an otherwise tight fiscal climate.

The venture capital industry is clearly interested in these emerging technologies as well. Despite a widespread perception that investment-worthy nano firms are still few and far between, NSTI and MTC estimates that in 2002, the venture capital community invested nearly $20 million in Massachusetts nano-startups, narrowly defined (nanoscale technologies), and as much as $140 million in Massachusetts start-ups, more broadly defined (nanoscale technologies and related fields, such as biotechnology and semiconductors).

Continuing advances in science are what drive the belief that nanoscale technologies are a source of future economic growth. More specifically, parallel advances in several fields of science and technology are what make the entire field of nanoscale technology the object of great anticipation.

Many observers believe that the nanotechnology revolution began in earnest in the early 1980s as scientists invented tools such as the Scanning Tunneling Microscope and the Atomic Force Microscope, tools that allow them to both visualize atoms and to manipulate them. The invention of advanced microscopy techniques represented

1 nanometer = 1 billionth of a meter

Nano-scale technologies reference a scale from 1 nm - 100 nm

A volume 1 nm on a side (1 nm^3) would hold roughly 500 - 1000 atoms

Nanotech applications identified in the following industries: Energy, Electronics, Materials, Transportation, Environmental, Defense, Medical, Pharmaceutical

U.S. federal spending toward research funding: $3.7 billion over four years (authorized)

Japan and European Union (EU) each have similar research and commercialization federal spending to the U.S.

Summary

a major technological leap forward that made the concept of 'nanotechnology' possible.

In the meantime, breakthroughs in life sciences have made it possible for scientists to isolate the genetic building blocks of life, and thus to understand how nature itself creates nanoscale structures such as bone, proteins, and the internal mechanisms of living cells. Advances in computer science have made it possible to simulate, design and analyze the novel properties of materials at the nanoscale so that they can be harnessed in new devices. Progress in existing industrial techniques, such as chemical vapor deposition processes used in semiconductor manufacture, have made it possible to create precise features and layers of new materials of nanoscale dimension.

The parallel development of these and other technologies have now given researchers the capability to combine disparate technologies to create entirely new classes of products, including products that capitalize on extreme miniaturization (Circle A), products that yield extraordinary new properties (Circle B), and products useful for creating products (such as tools and instruments) through direct manipulation of matter at the nanoscale (Circle C). The intertwining of different technologies is a by-product of increasingly interdisciplinary research and development within universities and industry.

Readers will note throughout this report that interdisciplinary R&D is a major driver in virtually all of the most promising areas of nanoscale development. Massachusetts has extraordinary resources for interdisciplinary research and development, resources that should be nurtured to ensure the state's leadership in future nanotechnology-related business development.

Key Elements of Nanotechnology and their Implications for the Massachusetts Economy

This report makes a start on defining the nanotechnology community in Massachusetts. No assessment can be precise, at least as this early stage of nanoscale technologies and of new, nanotechnology-related firms. The Nano Science and Technology Institute (NSTI) and the Massachusetts Technology Collaborative (MTC) estimate that at least 100 companies now operating in Massachusetts are focused upon important nanoscale products or processes, but many of these firms may not readily identify themselves as 'nano firms'.

A solid assessment of the state's strength in nanotechnology begins with a survey of the research base in universities and research institutions. Massachusetts fares quite well, as this report will attest. Massachusetts has a deep and broad base of scientists and engineers in both academia and in industry that gives the state a distinct advantage in the interdisciplinary investigations that fuel the most promising work in nanoscale technologies.

Three other elements should be kept in mind.

First, nanoscale technologies will be enabling technologies. To paraphrase the BASF Corporation: nanoscale technologies will not be the products you buy, they will make the products you buy better. Thus, in assessing nanoscale technologies in Massachusetts, it will be important to assess their potential impact on a range of existing applications and existing industries that are critical to Massachusetts.

Second, nanoscale devices will only be made useful if they are integrated into products that can also be fabricated in great volumes, at reasonable cost. Nanoscale transistors must be developed that can actually be integrated into a device that can be mass-produced. Nanoscale devices for medical applications must be integrated into medical devices that can be manufactured in a safe and efficient manner.

Since many of the emerging nanoscale technologies are still largely experimental, many of the most basic issues of product engineering and manufacturing are not yet resolved. This creates both a risk and an opportunity for the Massachusetts economy: Until engineering and manufacturing issues are resolved, investment in nanoscale research and development will remain highly speculative, just as investment in biotechnology was in its early stages. (One can argue that the biotech industry now has a track record for product approval and manufacturing. At the time of this report, there is little in the way of a 'nano track record'.).

Nanoengineering and nanomanufacturing are potentially significant business opportunities for Massachusetts. The state's technology community has a long tradition in the invention of tools, instruments, and manufacturing processes to serve industry.

Finally, nanoscale technologies and new 'nano firms' may prove uniquely susceptible to commercialization by acquisition from existing firms, and many of these firms will be located out of Massachusetts, if not outside the U.S. Much of the nanoscale R&D is happening within academic laboratories, and will be made available for commercialization through licensing.

As noted above, nanoscale technology will be enabling technology, useful only when it is adopted for the enhancement of existing products or manufacturing processes. Nanoscale technologies will frequently be developed within new firms as 'intellectual property plays', meant for eventual licensing or outright sale to outside firms. Thus, in assessing the strength of the Commonwealth in nanotechnology over the long term, we need to monitor the effectiveness of technology transfer from universities, other research institutions and small firms. We should encourage the state to maintain an environment in which cutting-edge research is translated into new technology through the creation of new, Massachusetts-based firms, and through its adoption by Massachusetts-based firms. Although it is too early to assess how well Massachusetts firms are adopting nanoscale technologies because few nanoscale technologies are ready for adoption, we can start to assess how well the state is supporting the translation of nanoscale research through the development of young, entrepreneurial firms. On this score, the state has made a good start, generating venture capital flows of approximately $20 million in 2002, or as much as $140 million in nanoscale technologies and closely related fields.

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Nanotechnology and Its Impact on Industry

Introduction

Technological advances of the past ten years have revolutionized our ability to manipulate matter at the nanometer length scale. This ability to engineer atoms, molecules and their arrangement, allows an unprecedented control of the fundamental behavior of matter, facilitating elegant solutions to previously intractable problems.

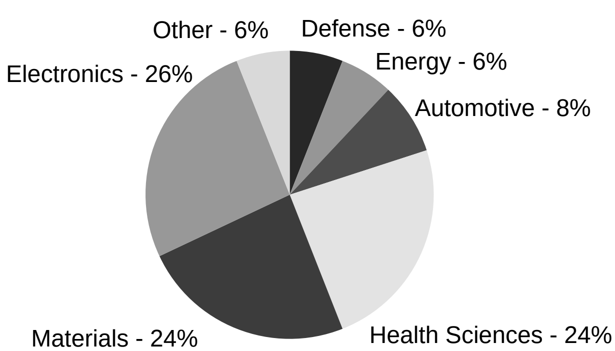
The interdisciplinary nature of nanotechnology is driving progress in the materials, instrumentation, electronics, healthcare, defense, sensors, manufacturing, energy, and environment areas. Indeed commercial products already exist that utilize these enabling processes and technologies. Both incremental and revolutionary advancements are to be expected from these enabling technologies.

The pervasive nature of nanotechnology is illustrated in Figure 1, which shows the associated industrial sector for attendees of the 2004 Nano Science and Technology Institute (NSTI) Nanotechnology Conference and Trade Show.

Impact of Nanotechnology on Massachusetts Industry
Nanoscale Technology Companies in Massachusetts

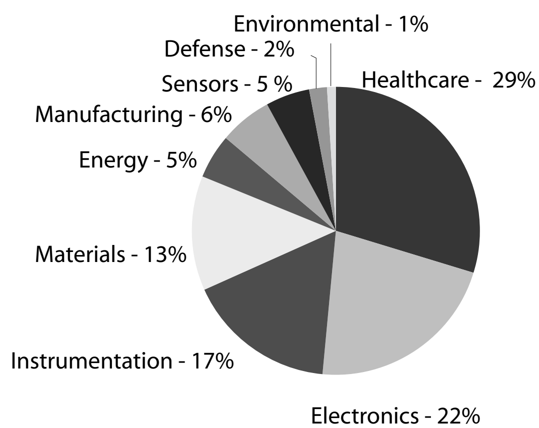
Nanoscale technologies are both impacting existing industries and creating opportunities for new company development. As of February 2004, Massachusetts was home to over 100 companies using or developing nanoscale technologies. More than half of these companies were focused in the areas of Healthcare (29%) and Electronics (22%), which reflects the state's historic strengths in both the Life Sciences and Computer Hardware and Software industry clusters. Instrumentation (17%) and Materials (13%) focused nanoscale technology companies are also well-represented in the state. Overall, Massachusetts has strong diversity in nanoscale technology business development, with all nine industry focus areas (as identified in the chart below) being represented in the state.

Associated Industrial Sector for Attendees of NSTI-Nanotech 2004



Source: Nanotech2004 Conference, Nano Science and Technology Institute (NSTI)

Distribution of Massachusetts Companies Using or Developing Nanoscale Technologies, February 2004



Source: Massachusetts Technology Collaborative and Nano Science and Technology Institute Research

Industry Summaries

The following section, with contributions from experts in their respective fields, summarizes how advancements in nanotechnology are impacting the materials, instrumentation, electronics, healthcare, defense, sensors, energy, manufacturing, and environmental fields.

Nanotechnology and MATERIALS

The materials industry has worked with the components of nanoscale particles and structures for quite some time, with applications ranging into most every existing industrial sector. With recent advancements in nanoscale design tools and characterization capabilities, the ability to rationally design new material structures and function is becoming a reality. These added capabilities open the door to a large range of potential new nanostructured materials by design. The focus of this summary is specifically on the definition and potential applications of these nanostructured materials.

Nanostructured materials are particles having average grain size on the order of a nanometer (10^{-9} m). In other words, materials that contain grains or clusters between 1 and 100 nm can be considered as nanostructured. Owing to their small size and high surface area to volume ratio, these materials have unique mechanical, optical, electronic, electrical and mechanical properties. Mechanical properties include super plasticity, improved strength, hardness and reduced elastic modulus. Nanostructured materials can exhibit higher electrical resistivity and lower thermal conductivities than bulk materials.[1] See Endnotes.

Nanoparticles interact with their surroundings quickly and are very reactive. For example, metal nanoparticles tend to oxidize rapidly when exposed to air. Applications of metal nanoparticles encapsuled in graphite shells have been recognized. For instance, magnetic materials (such as metallic Ni, Fe and Co) encapsuled inside graphite shells can be used in recording media, ferro fluids or magnetic tagging elements. When these nanocapsules are injected into biological systems, they can be used as a drug or tracing delivery and monitoring system.[2] Other major technology areas of nanomaterials are in advanced composite materials, microprocessors, catalysts, high-energy batteries, automobile and aerospace components, optical devices, radiation shielding, and energetic materials. The main use of nano-energetic materials is in explosives, as well as in gun and missile propulsion.

Nanomaterials have become integral components of products such as strong and lightweight plastic composites, electrically conductive coatings, and other ceramic coatings that have higher wear resistance and enhanced toughness. Nanomaterials are vying for new markets in food packaging, industrial processing, and electronics.

Nanoclays are materials that occur naturally and have plate-like clay particles that can be blended into plastics to form composites with improved strength, heat resistance, barrier properties and flame retardancy.

Multi-walled carbon nanotubes are hollow cylinders of interlinked carbon atoms, which arrange themselves in hexagonal rings like chicken wire and are nested inside one another. Carbon nanotubes have applications ranging across semiconductors, electronic memory and drive products, composites, and medical diagnostic and delivery systems. They also are used to make plastic automobile body panels conductive so that they can be spray painted electrostatically which therefore eliminates the need for a costly primer coat. Preliminary scientific reports revealed that carbon nanotubes are good flame-retardants in polyethylene and polypropylene.

Considerable work is yet to be done to develop and improve processing techniques of nanopowders efficiently. In most production processes of nanoparticles there still remains a need to control nucleation and grain growth, develop a technique capable of controlling particle agglomeration and size distribution, develop methods to scale-up systems effectively and shorten their manufacturing cycle time. However, the potential economic impact into most every industrial sector is evident by the vast range of affected applications and products already identified.

Amit Kurupathi, Nano Science and Technology Institute

Dr. Matthew Laudon, Director, Nano Science and Technology Institute

Nanotechnology and Massachusetts Materials Industry

Massachusetts is not a national leader in the materials industries, at least in terms of overall employment, but several materials-related industries maintain a significant presence in the state's economy. According to statistics compiled by the Institute for Strategy and Competitiveness at Harvard Business School, the chemical products industry employed approximately 9,700 in the state as recently as 2001, although employment in the industry had declined by 3.36 percent during the previous decade. Approximately 25,000 people worked in the state's plastics-related industry, many in fabrication of plastics products, as distinct from plastics-related materials. Despite the overall decline in the entire U.S. textile industry, over 9,000 workers were still employed in textile-related industry in Massachusetts in 2001, placing the state ninth among the fifty states.

Despite the relatively modest size of the materials-related industries in Massachusetts, several materials firms in the state are leaders in markets that could figure heavily in the future development of nanoscale materials and nanoscale products. Cabot Corporation, headquartered in Boston with a research headquarters in Billerica, is one of the world's leading formulators and producers of carbon-based materials. The state is also home to several smaller firms and new start-up companies that have established a presence in carbon-based nano-materials. The firms include Hyperion Catalysis of Cambridge (the first firm to offer commercial carbon nanotubes), Catalytic Materials of Holliston, and NanoLab, Inc. of Newton. Meanwhile, the General Electric Company continues to maintain its worldwide headquarters for plastics and plastics research on its Pittsfield (MA) campus.

Nanotechnology and INSTRUMENTATION

The successful advancement over the next quarter century in the ability to understand, create, and manipulate objects and processes on the nanoscale will depend on the development of the necessary tools and instrumentation to measure, characterize, and visualize the nanoscale environment. A key element of the burgeoning growth in nanotechnology is the design of functionality into nanoscale objects. To confirm the operation of new nanomaterials, and especially to characterize all the steps of fabrication and modification, nanoscale characterization tools are absolutely critical. New nanoscale materials, whether they be quantum dots, carbon nanotubes, hybrid semiconductor/viruses, or new functional nanoparticles for coatings will all require nanoscale identification and scientific characterization. As transistor components in electronics, magnetic elements of hard drives, and optical elements in photonic devices shrink to tens of nanometers, and the interfaces between functional materials to a single nanometer, determining the location and chemical composition of each atom will become more and more critical to the fabrication and operation of the devices.

From the time man first invented tools, instrumentation development has always preceded discovery and subsequent technological advancement. In imaging, X-ray diffraction was 60 years old before it was used to unravel the mystery of DNA; electron microscopy was 40 years old before it was used to discover carbon nanotubes; and optical microscopy was 300 years old before it was used to peer inside a cell. But in a few years following their development, scanned probe techniques laid to rest a two decade old argument about the surface structure of silicon. The pace of instrumentation development must keep up with the rapid changes in nanoscience and nanotechnology.

Unfortunately, many tools for nanoscale imaging and characterization do not currently exist. While we create more and more technological advancement dependent upon nanoscale interactions, our ability to locally measure these interactions is falling far behind. We cannot determine the three dimensional location and chemical composition on an atomic scale of any object or material. We are starting to come close with new high-energy Scanning Transmission Electron Microscopy (STEMs) that correct for aberrations, but only for hard and robust materials that will take the large energy deposition. We can create atomic images with scanned probe microscopy; measure the types and positions of atoms, but only on the surface. Information just below is as yet, unattainable. In the optical microscopy and spectroscopy regime, we have developed new tools to overcome the diffraction limit, but are still in the tens to hundreds of nanometers for resolution, except in special cases.

What are today's grand challenges and how will they be met? In nanoelectronics, nanomagnetics, and hard materials, the grand challenge is in three dimensional, chemically specific, atomic scale imaging. In 10-20 years, we would like to be able to create a complete map of a device or material, preferably under operating conditions, that yields the location and coordination of every atom. In hard material systems, the main approach is in the continued development of high energy, short wavelength, beams of particles, specifically photon, electron, ion, and neutral atom microscopy. The difficulties lie in the development of techniques to provide three dimensional imaging. In biological and soft materials systems the challenges are compounded by the fragility of the system, and its inability to absorb high amounts of energy before death or destruction. In these systems, optical techniques still reign, largely because they are non-destructive, depositing minimal amounts of energy. A grand challenge in bioimaging could be to image the process of transcription in vivo, or image a single protein from its creation to its action elsewhere in the cell. For these challenges one requires nanometer resolution inside a heterogeneous three dimensional object that is changing on short time scales and cannot take much energy deposition. Single molecule microscopy and new interferometric techniques may become the way to go here.

The State of Massachusetts is rapidly developing new nanoscale instrumentation and characterization capability in its universities, major industries, and small start-up companies. At Harvard University and MIT, a joint Nanoscale Science and Engineering Center is developing a variety of scanned probe tools to visualize the flow of electrons in nanoscale electronic systems, and new nanocrystals as bright tags for imaging in magnetic and biological systems. At Boston University, a Nanoscale Interdisciplinary Research Team has succeeded in using solid immersion microscopy techniques for imaging inside computer chips; are developing interferometric fluorescence for nanoscale imaging of subcellular processes; and are applying ultra-fast lasers for acoustic measurements of nanoscale mechanical properties. In addition, major instrumentation industries like Thermo Electron Corporation are enhancing their already large presence in spectroscopy, microscopy, and characterization.

Dr. Bennett Goldberg, Associate Chairman for Condensed-Matter Research, Boston University

Nanotechnology and Massachusetts Instrumentation Industry

A revolution in analytical instruments made possible the ongoing revolution in nanotechnology. With the invention of Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (ATM) twenty years ago, it became possible to visualize matter at the molecular and atomic level, and thus to begin the exploration of nanoscale structures that has led to the development of nanoscale technologies. Analytical instruments that measure chemical vapor depositions, light sources, and other phenomenon are increasingly central to the development of commercial nanotechnologies. Massachusetts has been a center of the analytical instrument industry for many decades. Massachusetts-based companies such as Thermo Electron Corporation, Waters Corporation, and PerkinElmer are leaders in the field. Harvard Business School Professor Michael Porter has estimated that over 60,000 people work in the analytical instruments industry cluster in Massachusetts—the second largest such concentration in the United States. The growth of nanotechnology-related industry throughout the world should create new market opportunities for the state's instrumentation companies in the years ahead.

Nanotechnology and ELECTRONICS

The electronics industry is one that is quite used to working at the nanoscale, and has been manufacturing features measured in nanometers for many years. Moving beyond this and into the field of nanotechnology, where benefits can be reaped from forces and effects only possible at the nanoscale, however, will allow the industry to solve many existing problems and create new products not formerly possible. It is for that reason that almost all of the major semiconductor firms have been expanding their research and development efforts and that startups such as Nantero (nonvolatile random access memory using carbon nanotubes) and NanoCoolers (heat reduction technology for microchips) are receiving substantial venture funding.

Nanotechnology holds the promise of allowing the progress now expected of the semiconductor industry to continue for decades to come by permitting devices to be manufactured at sizes too small to be feasible with current technology. For example, molecular self-assembly is being investigated as a replacement for lithography at feature sizes below 22nm, silicon nanowires with a diameter of 1-2nm are being explored as potential transistors for use in faster microprocessors, and carbon nanotubes with a diameter of 1-2nm are being developed for use in memory devices that will finally allow computers to boot instantly. The devices being made could not be made without nanotechnology, as they would not operate above the nanoscale: Nantero's nonvolatile random access memory depends on (so-called) van der Waals forces to retain data even when the power is turned off, IBM's nanotransistor relies on nanotubes as part of a channel, and Molecular Imprints' nanoimprint lithography process uses masks with nanoscopic features. What this means is that the electronics industry will benefit not just by having cheaper devices, but also by providing more value in their products: electronic devices that are smaller, lighter, use less battery power, and are substantially faster too.

For these reasons, nanotechnology is clearly expected to be a core competency for every manufacturer in the industry for decades to come.

Greg Schmergel, Co-founder, President & Chief Executive Officer, Nantero

Dr. Brent Segal, Chief Operating Officer, Nantero

Nanotechnology and the Massachusetts Electronics Industries

Employment levels in the electronics industries of Massachusetts have fallen in recent years, as they have in the U.S. as a whole, but electronics industries remain a vital part of the state's technology economy and Massachusetts is a national leader in several categories.

MTC's annual *Index of the Massachusetts Innovation Economy* tracks two large, composite industry clusters that encompass many of the electronics-related firms in the state. Both clusters, the computer and communications hardware cluster and the software and communications services clusters, remain very highly concentrated in Massachusetts as compared to the U.S. economy in general. [1]

The American Electronics Association annual rankings show that in several industry categories of particular, long-range import to nanotechnology, Massachusetts remains among the national leaders (as measured by employment).[2] These categories include the electronic components industry (7th in the nation, nearly 12,000 workers in 2002); semiconductors (6th in the U.S., 10,500 workers); defense electronics (7th, 5300 workers); measuring and control instruments (2nd, 22,000 workers); electromedical equipment (7th, or 3100 workers); and photonics (3rd, or nearly 4000 workers).

Nanotechnology and HEALTHCARE

Advances in nanotechnology will usher in a new era in healthcare innovations, which will provide new tools in the war on cancer and other diseases, provide point-of-care and wearable diagnostic and therapeutic devices, and will improve outcomes and ultimately drive down healthcare costs. The Draper Laboratory and the Center for Integration of Medicine and Innovative Technology are developing and facilitating a broad range of microsystems-based and nanosystems-based technologies aimed at improving healthcare.

Therapeutic fields such as drug delivery, tissue engineering, and drug discovery, will benefit greatly from advances in nanofabrication processes, nanostructured materials and nanoscale devices. Nanoscale pores in biocompatible capsules will deliver drugs in implantable devices while resisting immune response, to fight diseases such as diabetes. Novel nanostructured peptides will be used to mimic the in vivo microenvironment to foster the growth of replacement tissues and organs. Miniature assemblies of engineered cellular constructs will find use as a testbed for screening compounds for efficacy and toxicity in drug development.

In the area of diagnostics, new tools in the fight against cancer, heart disease and emerging infectious diseases will emerge from the nanotechnology revolution. Miniature implantable microsensors will be used to monitor patients for disease and to guide drug therapy. Nanomaterials and their assembly processes will serve as models for the investigation of disease development, and nanomechanical characterization techniques will explore the nature of ligand-receptor interactions in the diagnosis of cancer and other diseases. Nanostructured molecules such as dendrimers will be used as smart autonomous systems for diagnosis and treatment, by identifying cancer cells in vivo and releasing therapeutic agents locally. Nanowires only a few atoms wide will serve as building blocks for high-density arrays capable of screening for genetic mutations and biomarkers of disease.

Nanotechnology represents an emerging platform capable of revolutionizing healthcare by probing and treating disease at a much earlier stage and by interacting directly with the cellular and subcellular components involved in disease processes. The challenge for the future of NanoMedicine is to establish and grow strong collaborative teams that include the physicians and medical researchers who best understand the needs of their patients, and the scientists and engineers who are best able to respond to those needs with nanotechnology-based innovations.

Dr. Jeffrey T. Borenstein, Director, Biomedical Engineering Center, Draper Laboratory; Associate Director, Center for Integration of Medicine and Innovative Technology

Dr. Jonathan J. Rosen,Associate Director, Center for Integration of Medicine and Innovative Technology

Nanotechnology and Massachusetts Healthcare Industry

Massachusetts is a national center of medicine and healthcare technology, including the medical device and biotechnology industries. The emerging nanotechnology community in Massachusetts has a distinct interest in the development of nanotechnology for healtcare-related applications. In the future, this thrust towards 'nano-medicine' or 'nano-bio' applications could represent an important two-way opportunity for the state's economy: an opportunity to infuse nanotechnology into the new drugs, medical devices and other products produced by the state's life sciences firms; and an opportunity for the expertise of the state's enormous life sciences industry clusters to influence nanotechnology research in ways that will improve its potential for commercialization.

Like the nanotechnology community in Massachusetts, the life sciences community in the state draws on a large and deep pool of talent that crosses many disciplinary boundaries. In its 2002 *Index of the Massachusetts Innovation Economy*, the Massachusetts Technology Collaborative described the state's life sciences industries as the center of a 'super cluster'. Over 47,000 people work in the state's biotechnology, medical device, and healthcare-related research sectors, the fourth largest such concentration in the country after metropolitan New York, Los Angeles, and the San Francisco Bay area.[1] Over 25,000 people work in the state's medical device sector, and over 10,000 people are employed in the biotechnology sector.

The Massachusetts life sciences 'super cluster' leads U.S. performance in several areas. For most of the last decade, Massachusetts-based entrepreneurs have led the nation in the receipt of Small Business Innovation Research (SBIR) grants in the life sciences, although California-based firms have gained rapidly on Massachusetts in the last few years.[2] Massachusetts firms are second only to California in the total number of medical devices approved by the U.S. Food and Drug Administration (FDA) for marketing, and the state's biotechnology firms are third behind California and New Jersey in the number of biotech-engineered drugs approved by the FDA. The Massachusetts Biotechnology Council's strategic plan, released in early 2003, found that 8 percent of all drugs currently in the FDA drug approval 'pipeline' originate with Massachusetts companies, an historic high.

Nanotechnology and DEFENSE

The exploration of nanotechnology will create many new defense-related innovations, which are likely to have applications in the civilian sector as well. At the MIT Institute for Soldier Nanotechnologies, we see nanotechnology offering warfighters and others in hazardous situations key survivability capabilities through miniaturization, advanced information technology, and new materials properties.

Miniaturization will allow technology to become more mobile and more accessible to individuals and will enable multiple capabilities in smaller platforms. Microchip-sized sensors to detect chemical and biological threats will be integrated into clothing, reducing the need to carry bulky sensor equipment. Combining that with nanotechnology innovations in hazardous agent neutralization, drug delivery, and actuation of breathable-sealable fabrics can create a complete chem/bio sensing and protection system that operates automatically through a 'smart' battlesuit. Further miniaturization of computer technology will allow soldiers to access greater information through helmet displays and provide better monitoring of individuals' positions and physiological states from central command posts. Finally, miniaturization of protective technologies will reduce the load carried by soldiers, a critical factor in improving survivability.

Numerous other defense applications will benefit from new materials properties attainable through nanoscale engineering. Lightweight, non-bulky materials that protect the torso and extremities against bullets, shrapnel, and blast waves are a major goal. Creating materials with dynamic properties—those that can change shape or go from liquid to solid reversibly—might make possible automatic wound remediation, artificial muscle power, or smart armor systems, all incorporated into a clothing system. Nanoscale coatings just a few molecules thick will offer ways to create multifunctional surfaces—those that are water-and microbe-resistant, for example—without adding weight. Many of the technologies developed for protecting military personnel will also have significant value for homeland security providers, local police and firefighters, and other first responders.

Beyond developing the basic science of nanotechnology for defense applications, a key challenge will be discovering ways to affordably manufacture macroscale products in large quantities. Materials and device processing are critical to translating nanotechnology's promise to practicality. Conquering these challenges in the coming years will most certainly yield products for a wide array of defense and civilian applications.

Dr. Edwin L. Thomas, Director, Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology

Dr. William Peters, Executive Director, Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology

Nanotechnology and Massachusetts Defense Industry

Massachusetts has been a leader in defense industries since World War II, if not since the foundation of the Springfield Armory early in the 19th century. Employment in the state's defense firms has fallen steadily since the late 1980s, however, as a combination of defense spending cutbacks and the lure of cheaper labor in competitor states has reduced the state's defense-related manufacturing workforce. Nevertheless, employment in defense manufacturing and directly related instrumentation totaled about 42,000 in 2001.[1] Since World War II, the defense industry in Massachusetts has been strongly anchored in research and development (R&D), and in the development of new technologies and their integration into equipment and weapons systems for the military. Nanotechnology now represents a significant target for military research and development because of the new capabilities nanoscale materials offer for further miniaturization of military electronics and the incorporation of 'smart' materials into the clothing and equipment carried by soldiers in the field. MIT's Institute for Soldier Nanotechnologies (ISN) is a national center of excellence for the integration of nanotechnology into soldiers' field equipment, and Massachusetts-based Raytheon Company is one of the first, and largest, of the ISN's industry partners.

Military R&D will likely become an increasing source of support for the entire nanotechnology community in the state in coming years. After a decade of decline, defense-related research and development began to grow again during the last three years. Total defense-related R&D in Massachusetts grew at 3.5 times the national average from fiscal year 1996 to fiscal year 2001.[2]

Nanotechnology and SENSORS

The ability to engineer target-specific molecules facilitates the development of highly sensitive sensors. These devices are the physical interface to the natural world of systems monitoring the quality of air and water, the freshness of food, the presence of disease causing microbes, the existence of undesired by-products of combustion, and the quantity of pollutants. Application areas include homeland security, threat reduction, defense, environmental monitoring, chemical detection, food industry, and agriculture.

Chemical and biochemical sensing consists of a sequence of steps including sample collection, pre-concentration, amplification, separation, detection and transduction—all of which are improved by advances in nanotechnology. State of the art sensors often integrate inexpensive MEMS, microfluidic and semiconductor device fabrication technologies with the latest advances in materials, chemical and biochemical molecular engineering. The integration of these technologies, often in arrays, allows the volume manufacture of inexpensive high-performance sensors. These in turn provide high-quality data to smart systems that measure the chemical and biochemical quality of the environment.

The almost perfect specificity of antibody-antigen pairs, complementary DNA strands, protein receptor sites, and advances in biotechnology, have enabled the development of several innovations in the sensing arena. Biosensors involve two major components: first, a recognition element that senses the desired signal and second, a means of transducing this signal to a recording. With the increasing fear of possible bio-related terrorism, the need for easily and rapidly deployable sensors cannot be overemphasized. Nanotechnology provides a means to miniaturize these sensors and improve specificity and sensitivity.

In this regard, single walled carbon nanotubes[1] stand out with their high current-carrying capacity and functionalization options.[2]

Another important area of biosensing is intracellular imaging which has benefited from nanosized spectroscopic dyes[3] such as quantum dots that resolve issues such as stability and photo-bleaching that are encountered with typical fluorescent dyes. Such sensor array technology is also widely applied to study components in a solution with the most common example being the glucose sensor.

Biosensors also find wide application in the food industry,[4] especially with animal/fish products where contamination is a serious problem, whether freshness-related or due to malicious intent. Conventional methods for detecting microbial contamination have primarily relied on time-consuming enrichment steps, followed by biochemical identification. Biological sensors commonly used for rapid detection of micro-organisms use transducing techniques such as surface plasmon resonance (SPR), electrochemistry and acoustic wave technology. Robust, tissue biosensors using a hand-held fluorometric detector have been developed for the detection of airborne chemical warfare agents and simulants.[5]

These multi-disciplinary, multi-scale sensing devices are true demonstrations of the potential feasibility of integration between biology, electronics and materials to create complex nanoscale industrial systems. The application for these nanoscale sensing systems has potential significant benefits for health, environment, defense, agro and food industrial applications.

Dr. Srinivas Iyer, Los Alamos National Lab

Dr. Bart Romanowicz, Director, Nano Science and Technology Institute

Nanotechnology and ENERGY

Nano-engineered materials offer extraordinary new capabilities for the improvement of energy generation and efficiency. The use of high surface-to-area ratio carbon nanotubes in battery electrodes generates an increase in electricity output over traditional electrodes. This ability to increase the energy output from a given amount of material means that batteries will not only become more powerful, but that smaller and lighter batteries will become useable for a wider range of uses. A number of young Massachusetts-based firms are now engaged in developing next generation batteries for a wide variety of applications, at a wide variety of sizes.

Nanotechnology can be used to vastly improve fuel cell efficiency by utilizing nano-engineered materials. Essentially, fuel cells operate by catalyzing the conversion of hydrogen into energy as the hydrogen passes through a catalytic medium. The most advanced designs for next generation fuel cells involve the use of a polymer (plastic) membrane as the structure through the hydrogen passes and on which the catalysis occurs. Here again, the use of nano-engineered membrane materials may yield a significantly increased volume of hydrogen conversion, hence more energy.

Solar energy is the world's most abundant source of energy, of course, and nanotechnology is now driving radical improvements in the design and manufacture of solar (photovoltaic) cells. Today's traditional solar industry produces a high cost, small volume product that is economical to use only in specific settings. Again, nanotechnology is the enabling technology that can be applied to create a new generation of energy-efficient solar products. The Lowell, Massachusetts based solar energy company Konarka creates a photo-active, nanoscale material that can be printed on a variety of surfaces, including flexible plastics that can be manufactured in rolls, like newsprint. This photo-active material can then be cut up for uses both large and small: as a roofing material, as an interior wall material, as an energy source stitched onto or woven into a solder's backpack, and so on. The cost for Konarka's product are one third those of conventional photovoltaics, and the projected capital cost for manufacturing equipment and facilities is about one fifth of the prevailing cost for conventional solar cells, which are manufactured on silicon substrates in a process similar to that utilized to fabricate computer chips. The nano-engineered, photo-active materials pioneered by Konarka promise to turn the solar industry into a high volume operation, offering durable products for flexible and varied use that are ubiquitous.

The Massachusetts-based American Superconductor Corporation, a leading electricity solutions company, has successfully developed and filed a patent application for a nanotechnology-based manufacturing technique that delivers an immediate 30 percent increase in the electric current-carrying capability of the company's second generation (2G) high temperature superconductor (HTS) wire. This new nanotechnology process leverages AMSC's proprietary metal-organic chemical processing methodology by producing a dispersion of 'nanodots' throughout the superconductor coating of the company's 2G HTS wire. Nanodots are ultra-small particles of inorganic materials typically less than 100 atoms across. AMSC's 2G HTS wire is being designed as a form-fit-function replacement for today's commercial first generation (1G) HTS wire, but at two to five times lower manufacturing cost, which is expected to further expand the market for HTS applications.

Whether or not the new generation of clean and renewable energy companies identify themselves as 'nano' or not, they are part of what should be seen as a larger community of research and entrepreneurship in Massachusetts that has a vital stake in continued development of nanoscale materials and new processes to fabricate nanoscale products.

Daniel Patrick McGahn, Executive Vice President and Chief Marketing Officer, Konarka Technologies

Nanotechnology and MANUFACTURING

Increases in worldwide investments over the past few years have propelled the rate of nanoscience research breakthroughs to new levels. For these discoveries to lead to commercially viable products, it is important to address fundamental scientific barriers to nanomanufacturing, in parallel with the ongoing nanoscience research. To move scientific discoveries from the laboratory to commercial products, a completely different set of fundamental research issues must be addressed—primarily those related to viable commercial scale-up of production volumes, process robustness and reliability, and integration of nanoscale structures and devices into micro-, meso-, and macroscale products.

To address the needed basic discoveries and innovations in nanomanufacturing for achieving the full impact of nanotechnology, the National Science Foundation (NSF) recently hosted forums between industry, small business, and academia to address approaches to overcoming nanomanufacturing barriers and challenges. These workshop conclusions indicate that commercial products using nano building blocks are entering the marketplace. New processes are under development, but new ones are still needed for the manufacture of nanoscale products.

Nanotechnology and Its Impact on Industry

Industry Summaries

An NSF sponsored nanomanufacturing workshop organized by Northeastern University, University of Massachusetts Lowell and the University of New Hampshire identified the following nano-manufacturing products in progress, including:

- Hewlett Packard (HP): high density (6.4 Gbit/cm2) electronically addressable memory (Molecular Crossbar Circuits)
- Intel: nano-transistors for logic technology
- Lucent Technologies: rubber stamps and plastic circuits for electronic paper (plastic or paper display), 3D microfabrication via printing on curved objects, and large area nanoreplication with a flexible mold
- Motorola: nano elements of an OFET
- Triton Systems: nanoparticle-based chemotherapy, organic electronic materials
- General Motors (GM): high efficiency thermoelectric materials (modification of materials at the atomic level (nanoscale) to establish environmentally friendly cooling and recover electricity from exhaust heat

Each of these products has new nanoscale manufacturing barriers that must be overcome in order to realize efficient mass production.

Nanomanufacturing is in the conceptual stage of development. It faces many challenging barriers, technical and cultural. The primary technical barrier is the assembly of 3D heterogeneous systems. The current low reliability and yield for nanoscale devices is another challenge. Reproducibility and repeatability of nanomanufacturing will be essential. Another critical aspect is control of contamination and development of fault/defect tolerant devices. Finally, the lack of real time characterization methods hampers progress. To fulfill the true commercial potential of nanotechnology, research efforts are presently underway to overcome these barriers, preparing for high quality and low cost mass production of nano scale competents and enabling technologies.

Dr. Ahmed Busnaina, William Lincoln Smith Chair Professor and Director of the Nanomanufacturing Research Institute and the NSF Center for Microcontamination Control, Northeastern University

Dr. Joey Mead, Associate Professor, University of Massachusetts, Lowell

Nanotechnology and ENVIRONMENT

Nanotechnology has the potential to significantly impact the generation and remediation of environmental problems through understanding and control of emissions from various sources, development of novel 'green' technologies that minimizes unwanted by-products production, and remediation of existing waste sites and polluted water sources.

Nanoparticles are being examined for their use in sensors to monitor air or drinking water for the presence of toxins. Nanotechnology research includes sensors that can be used to detect chemical or biological contaminants. Applications of nanotechnology that reduce raw material usage, use of toxins and generation of wastes and effluents, as well as applications that effectively treat the waste streams can be of benefit to environmental protection. For example, W. Zhang of Lehigh University has developed a method of cleaning contaminated groundwater by using magnetic nanoparticles, composed of 99.9 percent iron and less than 0.1 percent palladium, a catalyst. Their extreme surface to volume ratio gives them extraordinary reactive abilities, and enables them to 'chase' toxins through the groundwater. When applied to water or soil contaminated with carcinogenic solvents, Zhang's nanoparticles remove chlorine and convert the solvents to harmless hydrocarbons and chlorides commonly found in table salt.

Considerable interest and data is presently being generated on the potential health and environmental impact of nanoparticle application and manufacture. Rice University's Center for Biological and Environmental Nanotechnology has teamed with industrial advisors such as DuPont and the Massachusetts based Cabot Corporation to investigate potential health and environmental benefits or implications of nanoscale technologies. U.S. Federal regulatory agencies are working with researchers and industry to formulate appropriate scientifically-based policies.

The importance of catalysts, which speed up the rate of chemical reaction to improve the environment, has long been recognized. With improved and advanced nanotech catalysts, it would be possible to make such processes more economical by being faster and efficient. The industries, which use nanostructured catalysts, are petroleum and chemical processing companies.

Nanoscale materials for Li battery cathodes such as aerogel could drastically increase capacity and cell life. It could be used to produce environmentally benign composite structures with enhanced properties and could be helpful to improve filtration systems. It also can produce lighter, smaller structures, resulting in energy efficient systems. The Massachusetts-based Aspen Aerogels produces nanoporous thermal insulation material for improved energy efficiency in applications ranging from aircraft to refrigeration to oil production. There are numerous potential nanoscale applications to improve energy generation and efficiency, resulting in secondary benefits on the environment.

Amit Kurupathi, Nano Science and Technology Institute

Dr. Matthew Laudon, Director, Nano Science and Technology Institute

Nanotechnology and Massachusetts Universities

Universities have played a vital role in the Massachusetts economy for decades, by training generations of highly-skilled people and by spinning off successive waves of innovative technology into industry. A 1994 study by the then-Bank of Boston found that MIT-related firms alone accounted for 10 percent of the entire economy of Massachusetts.[1] Academic researchers and academic research have been critical catalysts in the birth and growth of the region's biotechnology industry. Now, at the earliest stages of nanotechnology, universities seem destined to play a similar, perhaps even more dominant role, for two reasons:

Universities in Massachusetts Bring Broad and Deep Strengths in Relevant Science and Engineering Disciplines to the Global Competition for Nanotechnology Development

The sheer breadth and depth of the state's academic research community positions Massachusetts well for leadership in nanotechnology. As the sections of this report attest, 'nanotechnology' is neither a single technology nor a technology with a singular application. Much of the potentially revolutionary work in nanotechnology is driven by advances in fundamental sciences such as physics and chemistry, while many of the most innovative applications of nanotechnology will come about by interdisciplinary research that joins physicists, chemists, and materials scientists with engineers and life scientists. As a whole, the state's academic community is well represented across all disciplines, and has world-class strengths in many of them.

Universities throughout the U.S. Play an Increasingly Important Role in Technology Development within the U.S. Economy

The entire system of technological innovation in the U.S. is undergoing significant change in which universities seem destined to play a larger role than ever before.

Many major corporations that once financed significant, long-term research and development have cut back their commitments and are now more likely to invest in development than in research. Corporations are focused on short-term innovations (what one IBM executive has described as 'on demand innovation') that meet immediate customer needs and promise a short-term return on investment.[2] The job of developing innovations with radical, long-term consequence—a job that frequently necessitates years of costly investigation—now falls even more heavily on academic research institutions. This is not an entirely new phenomenon. From its inception, the biotechnology industry has been formed around entrepreneurial start-up firms spun-off from university-based research. The pattern can now be detected in the growing number of Massachusetts companies focused on nanoscale technologies that are based on intellectual property developed by scientists who remain active faculty members at area universities.

The Strengths of Massachusetts Universities

Over the last 25 years, as the software, computer networking and biotechnology industries grew in Massachusetts, university-based researchers in computer science, electrical engineering and biology became familiar figures in the state's economy. Nanotechnology now introduces (or reintroduces) the state to a broader set of players: physicists, chemists, chemical engineers, and materials scientists, and to a body of work in the state's universities that is frequently among the most advanced in the world. Massachusetts is home to a critical mass of competitive researchers and research in the most relevant scientific and engineering disciplines.

While Massachusetts ranks about 13th in population and workforce in the United States, it ranks 4th in the number of science and engineering doctorates awarded by its universities. It ranks second in the number of science and engineering post-doctoral students employed, according to the most recent data released by the National Science Foundation.[3] The state ranks 4th in the number of Ph.D. scientists and engineers residing in the state.

Research investment in the physical sciences is relatively high—third in the U.S. on a per capita basis, according to the Milken Institute.[4] The heavy investment reflects the ability of the state's university researchers to compete successfully for federal and industry funds. One example of significance to nanotechnology is in materials science. The National Science Foundation supports 28 research centers for materials science throughout the U.S. (the Materials Research Science and Engineering Centers, or 'MRSECs'). Three of the 28 are in Massachusetts, at Harvard University, the Massachusetts Institute of Technology (MIT), and the University of Massachusetts Amherst.

The most recent national assessment of academic quality within university doctoral programs is now nearly ten years old, but it gives an indication of the state's long-term strengths in fields relevant to nanotechnology. The 1995 National Research Council report on U.S. research-doctorate programs found that:

- Two of the top three U.S. programs in physics were in Massachusetts, (Harvard University #1 and MIT #3), with Boston University, Brandeis University, the University of Massachusetts Amherst (UMASS Amherst), and Northeastern University also among the leaders.
- Two of the top five programs in chemistry were in Massachusetts, (Harvard University #3 and MIT #5), with Brandeis University and UMASS Amherst among the leaders.
- MIT was the top ranked U.S. university in materials science, while UMASS Amherst ranked #7.
- MIT ranked #1 in the U.S. in biomedical engineering, #2 in chemical engineering, while UMASS Amherst ranked #21.[5]

University Research in Nanotechnology

Leadership in nanotechnology-related development starts with direction in knowledge and intellectual property, and Massachusetts-based researchers have already made a significant contribution. One recent measure is a study conducted by two University of California, Los Angeles (UCLA)-based economists, Michael Darby and Lynne Zucker, for the National Bureau of Economic Research. Darby and Zucker analyzed citations in scientific papers to isolate 'high impact' papers that documented 'breakthrough' discoveries relative to nanoscale research. They found that over half of the high impact nanotechnology papers are by U.S. authors, nearly sixty percent of whom reside in just ten metropolitan areas. Scientists in Greater Boston account for 8.7 percent of the articles, placing Greater Boston third behind Los Angeles/Santa Barbara (10 percent) and the San Francisco Bay area (9.6 percent).

"Like biotechnology, we find that firms enter nanotechnology where and when scientists are publishing breakthrough academic articles," according to Darby and Zucker. "Breakthroughs in nanoscale science and engineering appear frequently to be transferred to industrial application with the active participation of discovering academic scientists. The need for top scientists' involvement provide(s) important appropriability for biotechnology inventions, and a similar process appears to have started in nanotechnology."[6]

Inventing fundamental nanoscale devices is not the same as developing them for commercial production. If Darby and Zucker are correct, it will be particularly important for Massachusetts-based universities not only to succeed in generating fundamental scientific breakthroughs, but in producing the breakthroughs in device integration and fabrication that will become the basis for commercial production and the creation of a real nanotechnology industry and nanotech-related jobs. In this area, there are signs of strength for Massachusetts, as seen in the early success of the state's universities in the National Nanotechnology Initiative.[7]

Since 2001, MIT, Harvard University, and the University of Massachusetts Amherst have ranked among the top seven institutions in the country receiving research funds from the National Nanotechnology Initiative. At recurring points in time, the three universities constituted three of the top five institutions receiving NNI funds.

Two of the NNI's nine centers are located in Massachusetts, the **Harvard Center for the Science of Nanoscale Systems and Their Device Applications,** and the **MIT Institute for Soldier Nanotechnologies (ISN)**. The Harvard University team includes close collaborators at MIT and at Boston's Museum of Science (which provides K-12 curriculum development and outreach to K-12 schools). The MIT Institute for Soldier Nanotechnologies builds on close collaboration with the U.S. Army Soldier Systems Center in Natick, Raytheon Company, and other local defense firms.

Researchers at seven Massachusetts universities are recipients of Nanotechnology Interdisciplinary Research Team ('NIRT') awards from the National Science Foundation.

As nanotechnology becomes a high priority for federal investment, Massachusetts universities are responding by formulating ambitious plans for expanded nanoscale research. Viewed as a whole, the emerging strategy of the state's universities has at least three key features:

- The strategy continues to draw from the world-class strengths of Massachusetts researchers in fundamental science.
- It accelerates the trend towards interdisciplinary research and development—building a competitive advantage for Massachusetts because of the breadth of the state's scientific and engineering establishment.
- It is turning more aggressively towards the solution of critical engineering issues in nanoscale device development.

Detailed overviews of nanotechnology research at the state's universities can be found on the Massachusetts Nanotechnology Initiative web site at www.masstech.org/nano, but a few short examples illustrate the general thrust of research at the state's major research institutions:

Boston College

Boston College (BC) has made a strong commitment to its physics and chemistry departments in recent years resulting in a commitment towards nanoscale research in turn. Much of BC's nanoscale research is now coordinated through its new **Novel Electronics Materials Center**, and recent support from the National Science Foundation is funding work in advanced nanoscale imaging that combines features of atomic force microscopy with magnetic resonance imaging (MRI). Related work at BC entails development for molecular motors, biosensors and data storage.

Boston University

As one of the largest and most comprehensive private universities in the U.S., Boston University (BU) is already home to a wide range of nanoscale research projects that draw on faculty in the physical and materials sciences, in engineering and in the university's large medical school and teaching hospital complex. Boston University's **Nanoscience Working Group** includes researchers with strong interests in materials characterization and in the development of analytical instruments to visualize and measure pheneomenon at the nanoscale. Thus, current NNI-supported work at BU includes research on nanoscale optical techniques for investigating inorganic materials such as those used in the fabrication of electronic devices, and National Institutes of Health (NIH)-supported work on nano-optics for the imaging of living sub-cellular systems. Other BU research is focused on NEMS (nano-electromechanical systems), and on nanoscale materials for use in human therapeutics.

Boston University's current plans call for an increasing focus on 'nanotechnology integration', or interdisciplinary work that will not only characterize materials and generate the design of nanoscale devices, but also develop the engineering techniques and the tools necessary to fabricate nanoscale devices at commercially-viable levels of production and quality. BU's strategy calls for an initial focus on nanobiotechnology, including research projects that will advance the creation of nano-materials for medical uses, for biosensors, and tool development for the investigation of living tissue at the sub-cellular level.

Harvard University

The most prominent nanoscale research at Harvard University comes from its nationally-ranked faculties in physics and chemistry. Increasingly, it also comes from research conducted within its **Division of Engineering and Applied Sciences (DEAS)**, which the university has charged with an expanded mission to support interdisciplinary scientific and engineering research relative to the physical sciences. Nanoscale research drawing on the university's strengths in physics, chemistry, computer science and biology has found a home in expanded DEAS facilities.

Given the strength of the university in fundamental science, groundbreaking nanoscale research at Harvard University has resulted in the creation of early-stage enabling technologies that may lend themselves to widely disparate applications, including applications in both electronics and in the life sciences. Some of these early-stage enabling technologies have been spun-off into new, entrepreneurial firms that are examples of 'pure-play' nanotechnology companies.

As noted earlier, Harvard University is home to one of the first national nanotechnology 'centers of excellence' in the **Center for Science of Nanoscale Systems and Their Device Applications**. This center focuses on approaches to construct novel nanoscale devices and to study and measure the unique capabilities that result when such devices operate at the nanoscale. Beginning January 2004, Harvard University, along with thirteen other U.S. universities, kicked off the NSF funded National Nanotechnology Infrastructure Network (NNIN) providing a network of nanoscale fabrication facilities for member research and education programs.

Massachusetts Institute of Technology

With departments and research programs in a very broad range of both scientific and engineering disciplines, nanoscale research and development at the Massachusetts Institute of Technology (MIT) is emerging within departments, between departments and from informal collaborations among like-minded researchers who can take advantage of the sheer mass of talent that MIT brings together from so many different fields. Student interest in nanoscale research and in closely related fields such as MEMS (micro-electromechanical systems) has created what is known at MIT as a 'Tiny Tech' community.[9]

In recent years, MIT has begun to create focused research programs that concentrate explicitly on nanoscale research and development. The **Institute for Soldier Nanotechnologies (ISN)** is a center funded by a $50 million contract from the U.S. Army for research that sponsors projects leading to the incorporation of nanoscale materials into equipment and clothing for American soldiers. ISN projects are interdisciplinary and draw upon collaborators within the MIT community, from the U.S. Army Natick (MA) Soldier Systems Center, and from industry leaders such as Raytheon Company.

Laboratories with a specific nanoscale focus include the **Space Nanotechnology Laboratory** and the **Nanostructures Laboratory** (both within MIT's Microsystems Technology Laboratory), and the **NanoMechanical Technology Laboratory** (within the MIT Department of Materials Science and Engineering).

Northeastern University

Nanoscale research and development at Northeastern University is led by the university's engineering faculty and, thus far, is strongly focused on nano-electronics. The Northeastern University program builds on an existing base of research and teaching relevant to semiconductor design, fabrication and quality control, including the work of the National Science Foundation funded **Northeastern University Center for Microcontamination Control.** To sharpen its focus on nanoscale innovation, the university has created the **Northeastern University Nanomanufacturing Research Institute**, the first such research center among the state's universities to focus entirely on critical issues of nanoscale fabrication and commercial manufacturing.

Tufts University

Tufts University brings research capabilities in fundamental science, engineering, and in medicine to bear on nanotechnology. Nanotechnology at Tufts University is wide ranging: current nanoscale research at the university emanates primarily from its chemistry, chemical engineering and biological engineering programs, and includes projects for both nano-electronics and nanobiotechnology.

If there is an emerging theme at Tufts University relative to nanotechnology it is 'bottom up' nanotechnology for eventual use in medicine and healthcare applications. Several Tufts University research teams are focusing on the molecule-by-molecule creation of novel proteins and novel nanotubes for eventual use in drug delivery within the human body, and drug discovery in pharmaceutical laboratories. In 2003, Tufts University chemist Krishna Kumar was designated as one of the MIT Technology Review "100 Young Innovators" of the year for his work in nano-protein development.

The University of Massachusetts

The University of Massachusetts Amherst is a national leader among recipients of new research funding under the National Nanotechnology Initiative. Nanoscale research at UMASS Amherst draws on the university's strengths in physics, chemistry, chemical engineering and, most notably, on its nationally-ranked program in polymer science and engineering, including the programs of the **Silvio Conte National Polymer Research Center**. Research at the UMASS Amherst campus has broad potential impact, but the current strong emphasis is on nano-electronics. Nano-electronics will be the initial focus of **MassNanoTech**, a nanotechnology research center the university intends to develop over the next several years, and that will include a fabrication facility for the prototype production of novel devices.

The University of Massachusetts Dartmouth with its long roots in textile and fiber sciences, nanoscale research at UMASS Dartmouth is centered on the university's Textile Science Department, and focuses on both the uses of nano-fibers in textile materials and production techniques for nano-fiber production.

The University of Massachusetts Lowell, as at the UMASS Amherst campus, draws heavily on the university's longstanding strengths in polymer science and engineering in its focus on nanoscale technologies. The UMASS Lowell program also includes a strong emphasis on manufacturing-oriented engineering. Ongoing nanoscale research includes projects on nanoscale processing of plastics, self-assembling polymers for use in drug delivery, and bio-engineered nanoparticles for electronics applications.

Worcester Polytechnic Institute

As an institution with a historic tradition in engineering to support the state's manufacturing base, Worcester Polytechnic Institute's (WPI) effort in nanoscale research and development is rooted in years of effort in 'top down' nanotechnology, particularly for electronics-related applications. The WPI program is evolving in interdisciplinary directions, and in recent years its nanotechnology projects have shown a stronger and stronger orientation towards the bioengineering of nanoscale materials that have promise for eventual use in a wide range of medical and healthcare applications.

WPI's nanoscale research includes projects relative to nano-electromechanical devices (NEMS), nano-materials for photovoltaic films, and investigation in molecular electronics. But strategic recruitment of new faculty has sharpened the Institute's projects for fabrication of molecular and supramolecular devices aided by self-assembly processes. Much of this work is either originated by, or channeled through the **WPI Bioengineering Institute**, an interdisciplinary program formally launched in 2003, that has a unique mission to develop commercially-viable technologies for medical devices and other healthcare applications, while building a stronger life science industry base in the surrounding economy of Central Massachusetts. The Bioengineering Institute's program includes a strong alliance with its neighbor, the University of Massachusetts Medical School, and the medical school's corps of nationally-ranked life scientists.

Summary

Massachusetts universities bring enormous assets to the generation of new nanoscale technologies. The scope of nanoscale research in Massachusetts is broad, and the potential applications from the research expand far beyond the existing semiconductor industry. The diversity of Massachusetts expertise in nanoscale technologies gives the state a significant advantage in multi-sector intellectual property generation and commercialization.

In an economy that is increasingly focused on short-term investment for short-term results, reducing the innovation backlog is as important a task as building up the state's base of nanotechnology research, and it is a focus of concern at the universities. If Massachusetts is to fully realize the economic opportunity presented by the nanotechnology revolution, it must nurture effective initiatives to transform world-class research into world-class firms.

Thomas E. Hubbard, Vice President, Technology Development & Analysis, Massachusetts Technology Collaborative

Technology Transfer in Massachusetts

The importance of technology transfer and licensing is increasing dramatically with the growing reliance on U.S. universities and laboratories to provide technical advancements for global commercialization. New inventions and patents relative to nanotechnology are becoming a more important element in the technology licenses offered by local universities, and its nanotechnology researchers are a critical element of the universities' industrial liaison programs.

The strength and management of these technology sources will be important to the regional economic and workforce growth related to new technology commercialization. The Commonwealth's comprehensive and world-class set of technology transfer offices is expected to provide a powerful structure for generation and promotion of Massachusetts based technologies and companies.

The key points of contact at area universities include:

Boston College:
Office for Research Compliance and Intellectual Property Management (RCIPM)
(www.bc.edu/research/rcip/intelprop/)

Boston University:
Community Technology Fund (CTC)
(www.bu.edu/ctf/)

Harvard University:
Office for Technology and Trademark Licensing
(www.techtransfer.harvard.edu/)

Industrial Outreach Program/Division of Engineering and Applied Sciences (DEAS)
(www.deas.harvard.edu/indusandgov/)

Massachusetts Institute of Technology (MIT):
Technology Licensing Office (TLO)
(http://web.mit.edu/tlo/www/)

MIT: Industrial Liaison Program (ILP)
(http://ilp.mit.edu/ilp/)

Northeastern University:
Division of Technology Transfer
(www.research.neu.edu/tt/who.html)

Tufts University:
Office for Technology Licensing and Industry Collaboration (OTLIC)
(http://techtransfer.tufts.edu/)

University of Massachusetts:
Commercial Ventures and Intellectual Property (CVIP)
(www.cvip-umass.net/)

Worcester Polytechnic Institute:
Bioengineering Institute
(www.wpi.edu/Academics/Research/BEI/About/)

There have been a significant number of new nanoscale technologies passing from Massachusetts universities into commercialization. It would not be possible to list all of these successful nano-related technology transfers, so consequently, below is a partial list of commercialization activities.

- Lowell-based **Konarka Technologies** is one of the state's earliest nanotechnology-related start-up firms, and is built upon nanoscale technology for the creation of flexible photovoltaic devices that was pioneered by the late University of Massachusetts Lowell Professor Sukant Tripathy.
- Boston College Professor Zhifeng Ren has spun his carbon nanotube research into **NanoLab, Inc**., a Newton (MA)-based firm.
- Tufts University professor Dr. Regina Valluzzi is a co-founder of **Evolved Nanomaterial Sciences**, a Medford-based start-up firm that is developing nanoscale 'scaffolds' for use in drug discovery processes.
- A large number of nanotechnology-related start-up firms have recently emerged from the Massachusetts Institute of Technology (MIT). These include new companies focused on fuel cells and battery technology (**A123Systems and Lilliputian Systems**); nanoscale devices for use in drug discovery (**MicroCHIPS and BioTrove**); nanoscale materials for medical applications (**Angstrom Medica**); and nanoscale materials for industrial uses and consumer applications (**E-Ink, Nano-C**).
- Harvard University has produced numerous new companies based on nano-scale technologies. For example: 'soft lithography' techniques created by chemistry professor George Whitesides promise to create a variety of manufacturing techniques for the creation of novel products for both electronics and for drug discovery. **Surface Logix** is a start-up firm formed to commercialize Professor Whitesides' work in the drug discovery field, while a firm in formation, **EM Logix**, will commercialize soft lithography for electronic and optical applications. Harvard University chemistry professors Charles Lieber and Hongkun Park are founders of **Nanosys**, arguably the most prominent 'pure play' nanotechnology firm in the United States, and a firm largely focused on commercializing new semiconductor devices from inorganic materials. Notwithstanding its Harvard University connection, Nanosys now operates from headquarters in Palo Alto, California. **Nantero**, an early-stage firm focused on creation of nanoscale memory devices, was founded on work done by Dr. Thomas Rueckes in Professor Lieber's Harvard University laboratory; Nantero operates from facilities in Woburn, Massachusetts.

Nanotechnology and Venture Capital in Massachusetts

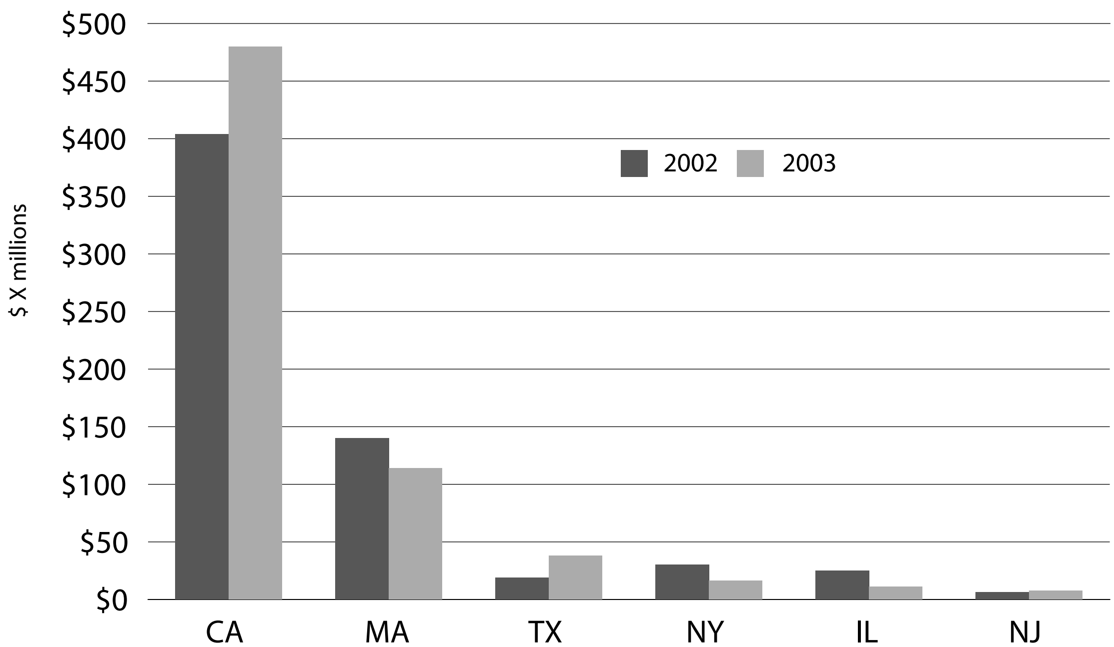
Venture capital is a critical funding source for companies that are using or developing nanoscale technologies, since these firms need significant investments over time for research, development, and commercialization. In 2003, Massachusetts companies using or developing nanotechnologies received $114.2 million in venture capital investments, second only to California, which had more than $480 million. In the United States, more than $900 million dollars was invested in companies using or developing nanoscale technologies, a three percent increase from 2002 ($879 million).

Several other states have also been attracting sizable nanotechnology-related venture capital investments, including Texas ($37.6 million), New York ($16.2 million), Illinois ($11 million), and New Jersey ($8.5 million). These six states accounted for 74% of all venture capital investments that funded companies that are using or developing nanoscale technologies in the United States for the same period.

In 2003, Massachusetts share of U.S. nanotechnology-related venture capital investments was 13% of the U.S. total (approximately $900 million), which is down slightly from the state's 2002 share ($140 million, or 16%).

While the tracking of nanotechnology-related venture capital investments is still emerging at the time of this report, this data shows that Massachusetts is one of the leading states in attracting private funding for companies using or developing nanoscale technologies.

Total venture capital investments in nanotechnology-related companies, Massachusetts and CA, IL, NJ, NY, and TX, 2002 and 2003



Source: PricewaterhouseCoopers/Thomson Venture Economics/National Venture Capital Association MoneyTree(tm) Survey prepared in cooperation with Small Times Media

Local, Regional and Global Competition: United States, Europe, and Japan

United States

Despite the fact that the very definition of the term 'nanotechnology' is still imprecise, nanotechnology is now the subject of serious global competition. The Organization for Economic Cooperation and Development (OECD) estimates that over 30 countries have established nanotechnology R&D programs in recent years. Nanoscale research nearly doubled from 1997 to 2000 in both the European Union and in Japan.[1] A recent presentation made by the coordinating office for the U.S. nanotechnology program reported at least 25 state and regional initiatives organized to promote nanotechnology and nanotechnology-related economic development.[2] Since 'pure play' nanotechnology firms are in their infancy (with the exception of some materials firms offering nanoscale materials), it is too early to find head-to-head competition among countries and states with regards to the creation, attraction or retention of nanotechnology firms. Instead, the 'nano competition' most relevant to Massachusetts is competition between states and localities in the U.S. for continued funding from the federal government under the National Nanotechnology Initiative (NNI), and among states and regions to create programs or services that will create the most 'nano friendly' environment for the establishment and growth of nanotechnology-related businesses.

Competition under the National Nanotechnology Initiative

As noted in this report on university programs, Massachusetts universities have been successful in winning support from the NNI since its formal launch in 2001. Harvard University, the Massachusetts Institute of Technology, and The University of Massachusetts Amherst consistently rank among the top seven recipients of funds from the NNI.

The National Nanotechnology Initiative (NNI) received a new, four-year authorization under the Nanotechnology Research and Development Act of 2003, signed into law by President Bush in December 2003. The Act authorizes the expenditure of nearly $4 billion for nanoscale research and development over the next four years, with approximately 60 percent of the funds to be disbursed to academic institutions. Small technology firms will directly benefit from the NNI as well, particularly through the Small Business Innovation Research (SBIR) program, which diverts 2.5 percent of all funds for competitive R&D contracts to competitions reserved solely for small businesses. On a per capita basis, Massachusetts consistently ranks as the most competitive state in the nation for receipt of SBIR funds.

The Nanotechnology Research and Development Act of 2003 authorizes but does not appropriate funds. The nearly $4 billion in research funds promised by the Act will be disbursed from the annually appropriated budgets of the individual federal agencies that support research and development, most particularly the Department of Defense, the National Science Foundation, and the National Institutes of Health. The National Nanotechnology Initiative (NNI) is not a standalone funding program of the federal government, but a coordinating device that acts to promote a balance portfolio of nanoscale research among federal agencies.

The NNI and its coordinating office (the Nanotechnology Coordination Office, a unit of the White House) have established five key 'investment modes' to guide federal agencies:

Investment Mode #1 supports fundamental scientific and engineering research ('Fundamental nanoscale science and engineering research'); grants are awarded primarily through conventional, peer-reviewed competitions.

Investment Mode #2 supports research in nine 'grand challenge' areas of particular relevance to the translation of nanoscale research into useful applications. Grants for 'grand challenge' research are also largely awarded through standard, peer-reviewed competitions.

The 'grand challenge' areas are:

1. Nanostructured Materials by Design
2. Manufacturing at the Nanoscale
3. Chemical-Biological-Radiological-Explosive Detection and Protection
4. Nanoscale Instrumentation and Metrology
5. Nano-Electronics, Photonics and Magnetics
6. Healthcare Therapeutics and Diagnostics
7. Energy Conversion and Storage
8. Microcraft and Robotics
9. Nanoscale Processes for Environmental Improvement

Investment Mode #3 supports 'centers of excellence', or multi-year research center grants such as those awarded to the Harvard University Nano Science Engineering Center (NSEC) and the MIT Institute for Soldier Nanotechnologies. Such grants typically are matched by substantial amounts of 'cost sharing' funds from the host institutions, and frequently by matching funds from state and local authorities as part of a larger effort to promote economic development related to the new research centers.

Investment Mode #4 supports research infrastructure, including a nationwide network of shared use facilities called the National Nanotechnology Infrastructure Network (NNIN); Harvard University is a lead institution within the NNIN, which is administered by Cornell University.

Investment Mode #5 supports research relevant to workforce preparedness and the societal implications of nanotechnology.

Nanotechnology initiatives in competitor states and regions

Nanotechnology initiatives now active throughout the U.S. span a wide range of activities and objectives, although many are administered by or hosted at universities, and serve to promote the expansion of nanoscale research. The more ambitious among them attempt to link ongoing academic research with technology transfer, new enterprise creation, and the eventual creation of new jobs based on nanotechnology-related innovation.

A few significant examples include:

Albany Nanotech:

Albany Nanotech is the name given to describe a coordinated program undertaken by the State of New York to establish the Albany metropolitan area as a global center for the development and production of the next generations of semiconductor devices. Commercial semiconductor devices are beginning to offer sub-100 nanometer feature sizes, and it is generally thought that the semiconductor industry will need to utilize nano-engineering to develop new methods of production that will yield even higher levels of performance. Through the

Albany Nanotech program, the State of New York has committed over $500 million to semiconductor prototype fabrication facilities at the State University of New York at Albany (SUNY-Albany), and to research and education programs at both SUNY-Albany and Rensselaer Polytechnic Institute. The SUNY-Albany investment has triggered matching commitments from the IBM Corporation, Tokyo Electron, Sony, and SEMATECH, which has created a SEMATECH North campus in Albany to take advantage of 300-millimeter wafer fabrication facilities at the Albany Nanotech complex. The Albany Nanotech program is also coordinated with the State of New York's overall economic development program in order to market sites in Greater Albany (including pre-permitted sites) to target companies in the worldwide semiconductor industry.

California NanoSystems Institute (CNSI):

CNSI was founded in 2002 as one of four new 'Institutes for Science and Innovation' located at campuses of the University of California to accelerate research and technology transfer from emerging technologies that promise to revitalize the California economy. CNSI is a joint program of the University of California, Los Angeles (UCLA) and the University of California, Santa Barbara (UCSB) and draws upon physical scientists and life scientists from both campuses. In its early stages, CNSI is building extensive new facilities in the heart of the UCLA science complex. The founding of CNSI and the state of California's commitment has also triggered the award of a NanoScience and Engineering (NSEC) designation from the National Science Foundation, which has awarded CNSI an $18 million, five year grant to create a research center in nano-manufacturing, (the CNSI Center for Scalable and Integrated Nanomanufacturing). Like Albany Nanotech, CNSI has an explicit mission in regional economic development. The CNSI charter calls for the center to promote commercial applications of technology devised by CNSI researchers, to provide incubator facilities and CNSI research teams for pre-commercial projects, and to seek out regional industrial partners for CNSI research and education services.

The Nanotechnology Institute/ Ben Franklin Technology Partners of Southeastern Pennsylvania:

The Nanotechnology Institute (The Institute) is a joint program of the University of Pennsylvania, Drexel University and the Ben Franklin Partnership, a program to promote technology-based economic development that has operated (under various modes) throughout Pennsylvania since the 1980s. The objective of the Nanotechnology Institute is to promote collaborative research among institutions and corporations in the four-state area around Philadelphia so as to establish a viable base for nanoscale product development and nano-business development. The Institute has mapped the region's research and industrial assets for nanotechnology and, with funding from state and federal sources, has begun to channel research funding to collaborative research teams targeting nanoscale innovations life science applications, including drug delivery, biosensors, and tissue engineering. The Institute's strategic plan calls for developing new programs that will accelerate the commercialization of new technology from the earliest stages of academic research to new venture creation, including the formation of specialized risk capital pools, entrepreneurial training, 'community of interest' networks, and appropriate workforce development programs.

Implications for Massachusetts

Massachusetts has a clear competitive strength in nanoscale research. The 2003 analysis of UCLA economists Michael Darby and Lynne Zucker for the National Bureau of Economic Research found that Greater Boston ranks behind only the metropolitan Los Angeles and San Francisco areas as a generator of 'high impact' scholarly papers relative to nanotechnology.

Massachusetts also enjoys a strong early advantage as a generator of new, nanotechnology-related firms. Venture capital investment in new firms with a strict nanotechnology focus totaled nearly $20 million in 2002, or about a quarter of the total investment in similar firms in California. Historically, venture capital investments in Massachusetts tend to total about one-quarter of the venture investments in California, so at this early stage, nanotechnology-related investments may be following the same, historical trend.

To maintain its leadership position, Massachusetts must continue to attract a high level of research investment in the years ahead, and nurture a high level of technology transfer into venture-backed firms. The state will need to continue its thus far successful performance in winning support from the National Nanotechnology Initiative.

To realize a true economic payoff from nanoscale research, however, Massachusetts will need to lead the nation in nurturing the translation of nanoscale technology to entrepreneurs and firms, and in supporting the growth of new firms. A noticeable target for attention should be the state's venture capital community—the second largest in the U.S.—and in leveraging the strength of venture capitalists and angel investors to the benefit of new and emerging nanotechnology-related firms.

The ultimate challenge for Massachusetts is in devising a comprehensive strategy that leverages all its points of strength in nanotechnology—the presence of thriving, interdisciplinary research; the availability of seasoned entrepreneurs; the interests of the investment community; establishing strong, two-way relationships with existing industry clusters that have a vital, long-term interest in nanotechnology; and the interests of universities, not only as sponsors of research, but as the proving grounds for new educational programs that will prepare the 'nano workforce' of the future.

Thomas E. Hubbard, Vice President, Technology Development & Analysis, Massachusetts Technology Collaborative

Local, Regional and Global Competition:

Europe

Europe's funding environment in nanotechnology is difficult to measure as main funding from the European Union (EU) is complemented in each country by national programs or organizations that support research as well as industrial research and development (R&D).

The 6th European Framework program (FP6) started in 2002 and one of its thematic priorities is nanotechnology. Based on current estimates, 1.3 billion will be devoted, over the course of four years, to a priority thematic area of research on nanotechnology and nanoscience, knowledge-based multifunctional materials and new production processes and devices. Two global objectives are defined: first, to stimulate the introduction of innovative nanotechnologies in existing industrial sectors; and second, to stimulate breakthroughs, which can lead to entirely new materials, new devices, new products and new industries.

Currently, Integrated Projects (IPs) and Network of Excellence (NoEs) are under negotiation for the thematic priority area Nanotechnologies and Nanosciences following the first FP6 call for proposals. The link below lists all IPs and NoEs:

http://europa.eu.int/comm/research/fp6/p3/firstcallresult_en.html

Most projects involve interdisciplinary research in the following fields:

- underlying nanoscale phenomena
- supramolecular architectures and macromolecules
- nano-biotechnologies
- nanoscale engineering techniques to create materials and components
- instruments, handling and control devices
- applications in areas such as health, chemistry, energy, optics and the environment

Based on a recent preliminary study of research activities (patents and publications), the following areas are 'hot topics' in the EU zone:

- structural applications (nanocrystals, nanotubes)
- IT challenge, information processing and data storage
- drugs challenge and nanobiotechnology (lab on a chip, nanoparticles)
- sensor applications (nanostructured sensors, molecular motor, nanowires)
- processing technologies (surface science, nanofabrication, lithography)
- generic long-term research (self-assembly)
- imaging, handling and supporting methodology (microscopy)
- polymer

The current budget of the FP6 puts considerable emphasis on two fields:

- nanobiotechnology related to genomics and proteomics (biochips, interface to cells)
- nanoelectronics related to IT society

Most EU countries have their own national programs or center of competences in nanotechnology. The most active EU countries in nanotechnology include:

Belgium: A USD 14 million project was launched in Wallonia to strengthen research efforts in nanotechnologies. Other programs are smaller and topical.

Great Britain: Britain's Department of Trade and Industry is increasing funding for a planned National Centre for Microsystems and Nanotechnology from USD 47 million a year to USD 80 million a year.

Denmark: National program aims to increases research, educate, and foster innovation in nanotechnology and nanoscience. USD 3 million per year for 3 years. Additional program (USD 10 million) in materials research.

France: Nanosciences program of USD 60 million focuses on research at 4 competence centers: CEA/LETI Grenoble, LAAS Toulouse, IEMN Lille, IEF/LPN Paris. Large government financing available for R&D projects with industrial partners interested in use of new processes and nanotechnologies.

Finland: Support for nanotech activities comes from other large funding programs in electronics, design, biotechnology and automation.

Germany: Programs to support research with SMEs in nanobiotechnology, in communications (quantum systems), silicon and optical technologies. Large basic and applied research program in material sciences (more than USD 100 million).

Netherlands: Active industry participation to the institute on polymers. Research programs currently in new production processes and metal welding. Fundamental research program on 4 years (USD 50 million) in the fields of electronics, materials, bionanotechnology, and process technology.

Switzerland: The priority program Top Nano 21 came to an end in December 2003 after funding more than 200 projects for a total of USD 36 million. Follow up funding will come from an agency CTI. Two of the twelve national centers of competences are focused on nanosciences.

European venture capitalists are also starting to look at and invest in nanotech companies. For example, 3i of England reported six investments in small tech companies. Smaller firms have started investing in the fields of fuel cells, solar technologies, and new materials. Nanodimension, a Swiss-based venture capital firm, is the first European investor focusing exclusively on nanotechnology opportunities.

Pascal Marmier, Advisor, Innovation and Entrepreneurship, Swiss House for Advanced Research and Education

Stefan Müller, EU Research Head Office

Local, Regional and Global Competition:

Japan

Japan began its foray into nanotechnology with the initiation in 1985 of a 'nanomechanism' project, leading to the discovery of carbon nanotubes in 1991. Though the technology was believed to be an important emerging technology, one with disruptive potential, it was not designated as one that deserved overwhelming public support at the time. That changed after the U.S. decided to implement its own national strategy to promote nanotechnology.

Japan's national nanotechnology program was established quickly after the February 2000 U.S. announcement of its National Nanotechnology Initiative. The over 80 percent budget increase by the U.S. from the previous year, from $270 million to $495 million, led Japan to quickly step up its own research and funding efforts. In 2001, Japan designated nanotechnology and related materials research as one top area under the new Science and Technology Basic Plan, promulgated by the Council for Science and Technology Policy ('Council'). Other key organizations in charge of nanotechnology national strategy include the Ministry of Economy, Trade and Industry (METI), and the Ministry of Education and its affiliated Nanotechnology Researchers Network Center of Japan ('Nanonet'), which plays a similar role to the National Science Foundation in the U.S., promoting basic research in nanotech and maintaining a national university based nanotechnology network. There is a strong perception in Japan, as was the case during the dawn of the computer industry several decades ago, that a national strategy will be required in order to find industrial applications for this technology. As a result, the level of coordination of policies to support commercialization in Japan, in partnership with industry, is outstanding. Funding levels are expected to reach approximately $1 billion for 2004.

The commercialization of nanotechnology in Japan is perceived to become a key component of potential economic growth, and an aide in the restructuring of the Japanese economy and companies in key strategic industries. The competition to commercialize and more stringent requirements on the part of government to more efficiently utilize public funding has created a vacuum leading Japan to be first to commercialize nanotechnology on a mass scale at the consumer level.

Traditional private sector policy making groups such as Keidanren (Japan's Federation of Economic Organizations) have prioritized commercializing nanotechnology. Keidanren's Industrial Technology Committee issued its first policy proposal in June of 2000 entitled "Nanotechnology Opens the Way to the 21st Century" only several months after the U.S. NNI announcement. This was followed up in the following year with another report ("The Future Society to be Created by Nanotechnology—n-plan 21") reviewing nanotechnology involved in the IT field, materials, measurement and processing. An industry association was formed toward the end of 2003, the Nanotechnology Business Creation Initiative (NBCI). The association's membership includes over 260 companies ranging from large firms and their suppliers in a variety of industries and start-up companies that were spun out of university research efforts.

In 2001, Hitachi Research Institute forecast that Japan's nanotech-related market would grow to 2.4 trillion yen by 2005, but it is believed that the rapid pace of development in Japan has already rendered that prediction as too conservative. The market may likely eclipse at least 10 trillion yen (over $90b) by 2010. Commercialization efforts have been targeted directly at Japan's Information Technology (IT) industries, taking a 'bottom up' approach. Nanotech market growth, approximately 85 percent of it, is expected to be the greatest in IT and electronics, new materials and processes over the next decade. Large companies have invested heavily in nanotech related research and development (R&D). In 2003, firms spent nearly 19.1 billion yen on nanotechnology R&D in the current fiscal year, up some 22 percent from fiscal 2002. For fiscal 2004, the figure will approach 23 billion yen, which would represent an increase of about 20 percent. In regard to R&D, a strong emphasis has been placed on carbon nanotubes and other nanomaterials for use in such applications as next-generation flat panel displays and fuel cells for electronic devices, environmental cleaning systems, high-capacity memory and nano-based glass and fibers. A great deal of effort and focus has been in the materials area since it is strongly believed that breakthroughs in this area are required before the construction of sophisticated, integrated devices built on the nanoscale can be initiated. These R&D efforts have led to an accumulation of key strategic patents related to nanotechnology, with Japan garnering significant 'market share' for patents relating to photo-catalysts, nano-composites, carbon nanotubes/fullerenes and quantum dots.

Though it is expected that most commercial applications will surface over a 5-10 year period, the commercialization of nano-materials by several industries, not only those related to IT, has already taken place, including those previously mentioned. Semiconductor and semiconductor equipment manufacturers will be introducing nanoscale technology that will aide in the development of the mass production of sophisticated LCD parts. Semiconductor companies also seek to overcome the 'red brick wall' problem, utilizing 50nm manufacturing technology with the aide of breakthroughs in nanotechnology by 2011. The competitiveness in the area of patents for nano-materials and electronics is a derivative of the country's desire to move up the high-value added scale of advanced manufacturing.

Japan's post-war highly successful use of industrial policy coordination between the public and private sector in high technology, coupled with the world's largest nanotechnology research budget, should guarantee the country a very strong competitive position in micro and nanotechnology research, development, and commercialization.

Louis Ross, Managing Director,
The Global Emerging Technology Institute, Ltd.

Nanotechnology: Recommendations for Regional Policy Makers

Will nanotechnology be the driver of the next economic boom? No one can be sure. What is certain is that many metropolitan regions across the country (and the world) are preparing for the era of good times brought from tiny things. The Massachusetts Nanotechnology Initiative is one of more than fifteen statewide or regional initiatives in the United States designed to promote nanoscale science and technology. At the national level, the President's 2005 Budget request provides for nearly $1 billion in funding for the multi-agency National Nanotechnology Initiative (NNI). Even so, the U.S. does not dominate spending on nanotechnology, and it has been matched or outspent by countries in Europe and Asia in what some characterize as an R&D 'dogfight'. Lacking a crystal ball to see the future implications of this global investment and competition in nanotechnology, I look back to former technological revolutions for lessons learned that might aid policymakers shepherd in the age of nanotechnology.

What analogies to the past are relevant? Biotech is sometimes referred to as the nanotech of the nineties. The analogy to biotechnology highlights the issues surrounding interdisciplinary research, a universally recognized characteristic of nanotechnological efforts. Comparisons to other historical precedents are also useful. Drawing an analogy to the assembly line illustrates that many of the benefits of nanotechnology will not be obvious to the ordinary consumer, since they will be hidden away in manufacturing processes. Likening nanotechnology to electricity suggests that it will create pervasive and long-lasting adjustments to the economy as the many facets of nanotechnology compound and interact, but that will take decades to effectuate.

Each antecedent from history is distinct and underscores a separate aspect of nanotechnology. However, all technological changes affect the workforce in one way or another. The first set of workers that nanotechnology has already affected are scientists and engineers—highly educated experts with the knowledge, skills, and brainpower to do research and development, whether basic or applied. National and local policies regarding funding of education and research, stipends and scholarships, and immigration and visas greatly affect the development of this work force.

Jobs and Productivity

The economic impact of a new technology can be analyzed in terms of two effects: (1) the creation of new products and services, and (2) the reduction of the cost of existing products and services. The invention of the daguerreotype in the mid 1800s represented the introduction of a new product that lead directly to the inception of the photography industry. In contrast, Henry Ford's improvement of the assembly line resulted in the latter effect, that is, it reduced the cost of automobiles (an item already enjoyed by the wealthy) by boosting the productivity of the workers manufacturing them. In practice, the two effects—novel products vs. cost reduction—represent two ends of a continuous spectrum. It is sometimes difficult to distinguish whether a new product or service is truly novel or instead the result of extreme improvements in efficiency. For instance, when the commercial electric refrigerator appeared, was it a novel product or merely an icebox that obviated the need for ice delivery? Further, a new technology may impact the economy in multiple ways that appear on both ends of the spectrum. On which end will nanotechnology be more heavily weighted? At this juncture it appears that nano will reduce the costs of producing existing products to a greater extent than creating new products.

One thing is certain. Nanotechnology will not create a single 'nanoindustry.' Instead, the technology will become integral to many industries—a general-purpose array of technologies that affects everything, analogous to electricity. Electricity enabled the modern economy and continues to sustain it. Just to name a few highlights: the electric telegraph revolutionized communications prior to the Civil War, electric machine tools greatly increased productivity in factories after World War I, and all consumer-grade computers use electricity to process information. Nanotechnology is likely to diffuse to some areas where electrification has not been important: (a) combustion engine automobiles, and (b) chemical based pharmaceuticals.

'Nano' is an umbrella term that embodies a collection of technologies, i.e., carbon nanotubes, molecular electronics, designer proteins, etc. In this sense, nanotechnology is comparable to information technology (IT). IT is a convergence of many separate technologies—personal computers, packet switching technology, fiber optic telecommunications—that allow us to effectively handle information as a commodity. For nanotechnology, the NNI states that its distinctive feature is that it binds together ultrasmall "devices and systems that have novel properties and functions because of their small and/or intermediate size." The power to boost productivity lies in this emergence of novel properties at the nanoscale. Manufacturing processes tend to be complex recipes of many ingredients and steps. Nanotechnology will provide a greatly expanded palette of new materials and techniques. Nanoengineers will find a multitude of opportunities to use this palette of emergent properties to streamline, and perhaps revolutionize, existing manufacturing practices in nearly all sectors of the economy.

Although nanotechnology can be expected to increase manufacturing efficiency, we shouldn't expect overnight gains in our pocketbooks. The economy took a long time to adjust to electricity and is still adjusting to Information Technology (IT). Just a decade ago, Nobel laureate Robert Solow said, "We see computers everywhere but in the productivity statistics." Now we see IT in the productivity statistics. Given the historical precedents, nano is unlikely to affect the productivity statistics for another decade at the minimum.

Introduction of a new cost-reducing technology requires investment in R&D, capital goods, and new labor skills. During this period, the highly skilled science and engineering (S&E) workforce is called upon to build and integrate the new technology into relevant industries. This is a boom time for jobs for the science and engineering workforce. In addition, there is need for supporting labor services, which will create job opportunities for other workers. Even the most high-tech industry hires many persons in sales, clerical and office work, and employs blue collar workers and service workers of different types. But as the technology matures, two competing processes begin to affect jobs. The technology (i) reduces the number of workers needed to produce a given level of output, and (ii) lowers the cost of products, which increases demand for goods and expands jobs. For the past 50 years in the United States the displacement effect has dominated the expansion effect in industries so that employment tends to fall in sectors that benefit most from technological advance. The share of employment in services, where technological change is modest, has grown most rapidly. The share of employment in agriculture, where productivity advance has been extremely rapid, has declined for decades.

Given the dominance of the displacement effect over the expansion effect, if nanotechnology raises U.S. manufacturing output, it is likely to do so without creating many new jobs in manufacturing. Due to the cost-reducing effect of nano, we should not think of nano as a job creating technology but rather as a productivity enhancing technology that permeates the economy. Nanotechnology will create some new jobs, but that will not be its main contribution to job growth. Its main contribution will be manufacturing efficiencies that improve real wages and living standards. These gains will in turn generate additional consumer demand for all sorts of products and thus contribute to the growth of employment. Still, nanotechnology will undoubtedly produce some novel products and the areas of the country which attract that production are likely to enjoy exceptional growth of labor demand and employment.

This suggests that regional policy makers should pay special attention to identifying those nanoscience advances that are most likely to engender brand new industries and to seek ways to give firms incentives to think about new products as well as processes. In addition, the potential future profits from nanotechnology will be spent and invested somewhere. The agglomeration of economic activity, whereby firms tend to buy products from other firms more in the cities and states where they are located, remains significant despite globalization. Regional policy-makers should encourage local firms to pay special attention to delivering services and goods to new nano-tech enterprises. The more quickly an area connects the new sector to the rest of the local economy, the more likely it will capture the gains from servicing the sector. Harvard University Professor George Whitesides has opined that nanotechnology will make memory storage devices so cheap as to be nearly free. What kind of investments will be needed to make products that take advantage of all that new nano-enabled capacity? How might firms in the region use those devices for producing or changing their own goods? What sectors or product lines are most likely to see the development of new products, which will be more job creating than will using the technology to reduce the costs of existing products? Policy makers should constantly revisit this question as the nanotechnology economy unfolds. There is potentially a great payoff from being the first to link nanotechnological advances to traditional production, from providing goods and services to firms specializing in nanotechnology, as well as from capturing early production of any truly new products.

Education and Training

Every new science or technology initiative requires its own supply of scientific workers, who must come from colleges and universities, foreign countries, or shift from other science-engineering activities. Successful R&D efforts rely on teamwork and communication. A complicating factor for the nanotechnology effort is the interdisciplinary (or multi-disciplinary) nature of the work, which requires communication across technical and scientific fields. But each of the sciences and engineering represent distinct ways of seeing the natural world, with different jargon, culture, and analytical tools. Nanotechnology workers must possess sufficient understanding of more than one discipline to promote efficient communication. Where can nanotechnology firms find this type of highly skilled workforce? The area that provides such a work force is likely to attract these firms more readily than other areas.

Presently there are few formal nanotechnology degree programs in the United States, with no baccalaureate programs, and only a handful of associates or graduate degrees. Worldwide, the sum total of formal nano-programs (called nanoscience, nanotechnology, or nanoengineering) numbers around a score. In the next 1 to 5 years, there will not be a great number of recent graduates holding 'nano' degrees to join the workforce. At the same time, there is no huge demand for workers identified specifically as nanotechnologists. Economists Paula Stephan and Grant Black of Georgia State University found that the number of distinct nano-related positions advertised in the journal Science grew from 37 positions in 2001 to 41 positions in 2002. For comparison, during the bioinformatics hiring bottleneck in the mid-90s, position announcements in Science doubled over the course of a year.

But activity in nanotechnology is growing. From 2000 to 2001, government funding for the National Nanotechnology Initiative grew by 28 percent to $600 million, and in the previous year government funding grew by 74%. Between $100 million and $500 million of dollars was invested in nanotechnology start-up companies in 2002, according to several financial news organizations. Many large manufacturing companies have begun significant nanotechnology efforts in the past few years. This growth in activity requires a corresponding growth in human resources performing nano-related work. Where is this supply coming from?

Universities have set up nano-institutes, supported by the federal government. For example, the NSF has awarded funds for six Nanoscale Science, Engineering and Technology Centers (NSETs), which have been established at Columbia University, Cornell University, Harvard University, Northwestern University, Rensselaer Polytechnic Institute, and Rice University. Other nano-institutes include MIT's Institute for Soldier Nanotechnologies and the California Nanosystems Institute. The hallmark mission of these centers-of-excellence is to bring together faculty members of different disciplines under a single organization to foster interdisciplinary research and collaboration in nanotechnology. Often, these researchers will retain a desk at their 'home' department. It is common for a nano-institute to have representatives from ten or more home departments. Typically, the institute managers choose scientists and engineers who have already demonstrated the ability to work outside the traditional departmental structure.

In the near term, industry will draw from graduate students and post-docs affiliated with the principal investigators of the nano-institutes. This population of workers will typically hold degrees in a traditional discipline, such as chemical engineering, solid state physics, or biochemistry. But they will have the advantage of immersion in an environment where interdisciplinary thinking and communication is fostered and perhaps even routine. As nanotechnology activity grows, industry demand may create the so-called 'seed-corn' problem in some of these centers. During the bottleneck of the bioinformatics hiring frenzy, there were complaints that the high salaries offered by firms was luring faculty away from universities and thereby reducing the capability for new student training. Descriptively put, the field was said to be eating its seed corn. Due to the potential for nanotechnology to permeate many industries, the relevance of skilled nanotechnology workers and new innovations may last for generations. Policy makers must insure that the long-term supply of talent and ideas is not sacrificed to satisfy short-term demand.

In this respect, the centers-of-excellence have an important secondary mission: educational outreach. The NSF funded NSETs are mandated to have formal educational outreach programs that come in various forms such as K-12 learning packets, museum collaborations, Research for Teachers internships, and Research for Undergraduates. Additionally, a new NSF program with a focus towards graduate and teacher training was recently announced for the FY 2004 NNI that will include Centers for Learning and Teaching (NCLT), each funded at $3 million per year for five years.

An important educational mission for nanotechnology centers-of-excellence has been largely unrecognized: retraining professionals. In the U.S., many scientifically trained graduates have left scientific fields in favor of positions in finance, management or other non-science related jobs. The NSF reported that in 1999 more than 50 percent of employed natural and life sciences and engineering degree holders worked in non-scientific jobs. Further, the post-doc position in traditional science fields is becoming an 'academic purgatory' rather than a stepping stone to professorship because the number of tenure track positions in academe are not growing to match the production of PhDs. The result is that many students have become disillusioned with the sciences as a career option. This supply of disenchanted students could be reenergized by the promise of nanotechnology. With the proper cross-disciplinary training, they could be prepared to meet the extra demand from nano-firms. Stephan has advised that before we commit to creating large new numbers of PhDs with nano specialties, we should work successfully to transition the current supply. Thus retraining centers are important to meet the initial peak in nanotechnology demand.

Retraining centers are also important for the long term health of the nano-based economy. Nano is a collection of distinct technologies that will interact, evolve and grow—perhaps for generations. In this scenario, a particular product or process will first garner investment capital (anti-cancer nanoprobes, for example) followed several years later by another nanotech related innovation (say molecular electronics). At the tail end of each of these mini-booms, a portion of the nanotechnology workforce must be ready to move quickly to the next big thing. Centers-of-excellence can provide workers with access to rotations in nanoscience laboratories, either before their first job, or for retraining between jobs.

Computational biology has another lesson about the nature of interdisciplinary research that is relevant to nanotechnology. Stephan and Black posited that during the hiring bottleneck in bioinformatics a plausible fix to the shortage of individuals would have been to take young life scientists and turn them into computational biologists—or to take those with degrees in mathematics or computer scientists and augment their education in biology. These strategies failed because young biologists tend to lack quantitative aptitude, while the programmers and modelers were difficult to recruit. The latter already enjoyed relatively high salaries, making the prospect of extra schooling an effective disincentive.

Naturally, students with quantitative aptitude gravitate towards those fields that required quantitative skills. Physicists tend to be more quantitatively skilled than biologists, electrical engineers more so than agricultural engineers. However, in the nanotechnology workforce, where workers may be trained in several disciplines, it will no longer be so easy to identify a candidate's quantitative skill level. In this circumstance, one might be tempted to conclude that the entire nanotechnology workforce must possess strong quantitative skill. This is a mistake. Nanotechnology firms will require a mix, from numerically sophisticated product designers to the more hands-on lab scientists to technicians. They also will require persons with business and marketing skills, able to identify the potential new products that nanotech can bring to the economy. Nanotech education and retraining centers must design curricula tailored to quantitative aptitude, and industry managers must be take into account the right blend of quantitative skill-level among employees while providing proper incentive for potential workers to obtain retraining.

Regional Innovation

Local policy makers can influence many elements of technological infrastructure. For example, many states sponsor regional conferences to facilitate idea exchange, provide links between small businesses and potential partners, and promote start-up incubators in targeted technologies. Economic development policies must take into account the condition of the current technological infrastructure and target specific types of innovative activity complementary to the area's industrial composition. States can direct state universities into areas where scientific advances are more likely to pay off with industrial spillovers and jobs for the taxpayers who fund the universities. Research by a variety of economists has shown the payoff to a locality of attracting new high tech firms which has strong implications for regional policies toward nanotechnology.

To help quantify the effects of technological infrastructure, Grant Black of Georgia State has analyzed the locale of SBIR (Small Business Innovative Research) Phase II grants in the U.S.—using them as a measure of regional innovation. This analysis examined 273 metropolitan areas in the United States over the period 1990-95, and focused on the benefits to high-tech startups from, among other factors, knowledge spillover and agglomeration. Black concluded that the key benefit of regional technological infrastructure is knowledge spillover from research universities. The presence of R&D activity at local research universities was the strongest indicator of SBIR phase II activity. Start-up companies also benefited from the presence of local commercial R&D labs, but to a significantly smaller extent. The inference is that small firms rely heavily on the transfer of knowledge from larger research institutions, and this reliance is particularly skewed towards public knowledge sources like universities rather than, say, R&D activity in private industry.

Analysis of the biotechnology boom by Michael Darby and Lynne Zucker of UCLA corroborate the finding that academic institutions are the primary key to innovation. The most influential research universities are at the forefront of generating novel uncodified knowledge and are able to attract exceptionally productive scientists. They proposed that these so called 'star' scientists in academe transferred their knowledge to the commercialization process through collaboration with engineers or scientists in industry, or by founding their own start-ups. They concluded that "star scientists play a key role in regional and national economic growth for advanced economies, at least for those science-based technologies where knowledge is tacit and requires hands-on experience."

Even in times of increasing partnerships between corporations and university, basic research remains the essential element to technical infrastructure. Knowledge flows primarily from academic labs to industry. Industry firms do not readily profit from investing in basic science since the risks are high that any specific research effort will have no commercial value in any reasonable time period. But because the overall body of knowledge is so valuable, there is a temptation to allow industry to control it or to dictate the direction of academic research in order to bring faster returns. Some might argue that such a practice could even reduce the government's burden for funding academic science. This would be a dangerous strategy. Even if industry firms can afford to divert significant funds to university research, and even if they are very good at picking research topics, firms have a strong incentive to restrict the knowledge that they help to create, which would result in a slowdown of the overall pace of basic research.

Intellectual property rights are an important incentive for individuals and firms to innovate. Yet they can also be an impediment to communication and knowledge sharing. Poor communication may be a factor in explaining why the advantages of agglomeration are not as robust as knowledge spillover. Agglomeration of economic activity can be indicated by the concentrations of related industry, labor, and population in a geographic area. Black concluded from his analysis of SBIR grants that agglomeration results in "no dominant pattern of influence on small-firm innovation at the metropolitan level," with varying effects depending on particular industry and indicator. It is not enough simply to attract companies or talent to a region. Individuals and firms must be encouraged to communicate with each other. This may be achieved informally with the establishment of regional nano-clubs. These are ostensibly hobby groups where like-minded folk can gather in a relaxed environment to share ideas on the latest in nanotechnology. A legendary example of this type of association was the Homebrew Computer Club, which counted among its members many leaders of Silicon Valley's microcomputer industry. Another potential initiative would be government sponsored meetings between business leaders in traditional sectors and those in the new nanotech area.

Massachusetts is well positioned to be a leader in nanotechnology, given the large number of high quality academic institutions in the state. The Boston metro area is consistently ranked in the top five hotspots of nano-innovation in the nation, typically alongside the San Francisco Bay Area, New York, Texas, and New Mexico. But innovation in Massachusetts is not restricted to the Hub. Besides the world class universities in Boston and Cambridge, other schools outside of Route 128 such as the University of Massachusetts at Lowell and Worcester Polytechnic Institute have received recognition for their research into nanoscale science and technology. The resources that provide knowledge spillover are strong in Massachusetts. Technology transfer is already recognized as an important activity by most research universities. It could be enhanced by providing explicit entrepreneurial training to students at the nanoinstitutes. The culture clash between MBAs and technologists can be deadly to small high-tech companies. A greater understanding of the management side of start-up companies can make researchers more comfortable sharing knowledge or founding their own ventures. In a complimentary fashion, centers-of-excellence should offer nanotechnology courses geared towards MBAs and executive education programs. This will alert regional firms to new opportunities, as well as adding some exciting science and engineering into the business curriculum.

Summary of Recommendations

If nanotechnology gets big, it will be big in Massachusetts, and conversely Mass will be big in nano. Here are some points to consider in thinking about the coming nano-economy:

1. Nanotechnology is foremost a collection of productivity enhancing technologies that will permeate many industries.
2. Business ventures should be nurtured that seek to reinvest nano-enabled productivity gains from established industries into the growth of new industries.
3. Nanotechnology education is a thorny problem due to its position at the intersection of many disciplines and is likely to work best in nano institutes.
4. Nano centers-of-excellence should provide retraining programs for professionals in order for members of the highly skilled science and engineering workforce to learn enough about other disciplines to collaborate effectively in interdisciplinary teams.
5. Establishment of hobbyist nano-clubs and other forums will promote idea exchange among individuals and also provide an informal mechanism for communications between firms.
6. The comparative advantage that Massachusetts enjoys in creating high tech startup companies can be enhanced by educating researchers about entrepreneurship while likewise educating MBAs about nanotechnology.

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For examples of recently-initiated efforts by Massachusetts universities to address the innovation backlog see the MIT Deshpande Center for Technological Innovation (http://web.mit.edu/deshpandecenter/); the Boston University Technology Commercialization Institute (http://management.bu.edu/newsletter/winter_03.) ; and the new University of Massachusetts Science and Technology Initiatives Fund, announced January 4, 2003. ("UMASS announces new $1 million fund to develop strategic technology alliances," at www.massachusetts.edu)

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