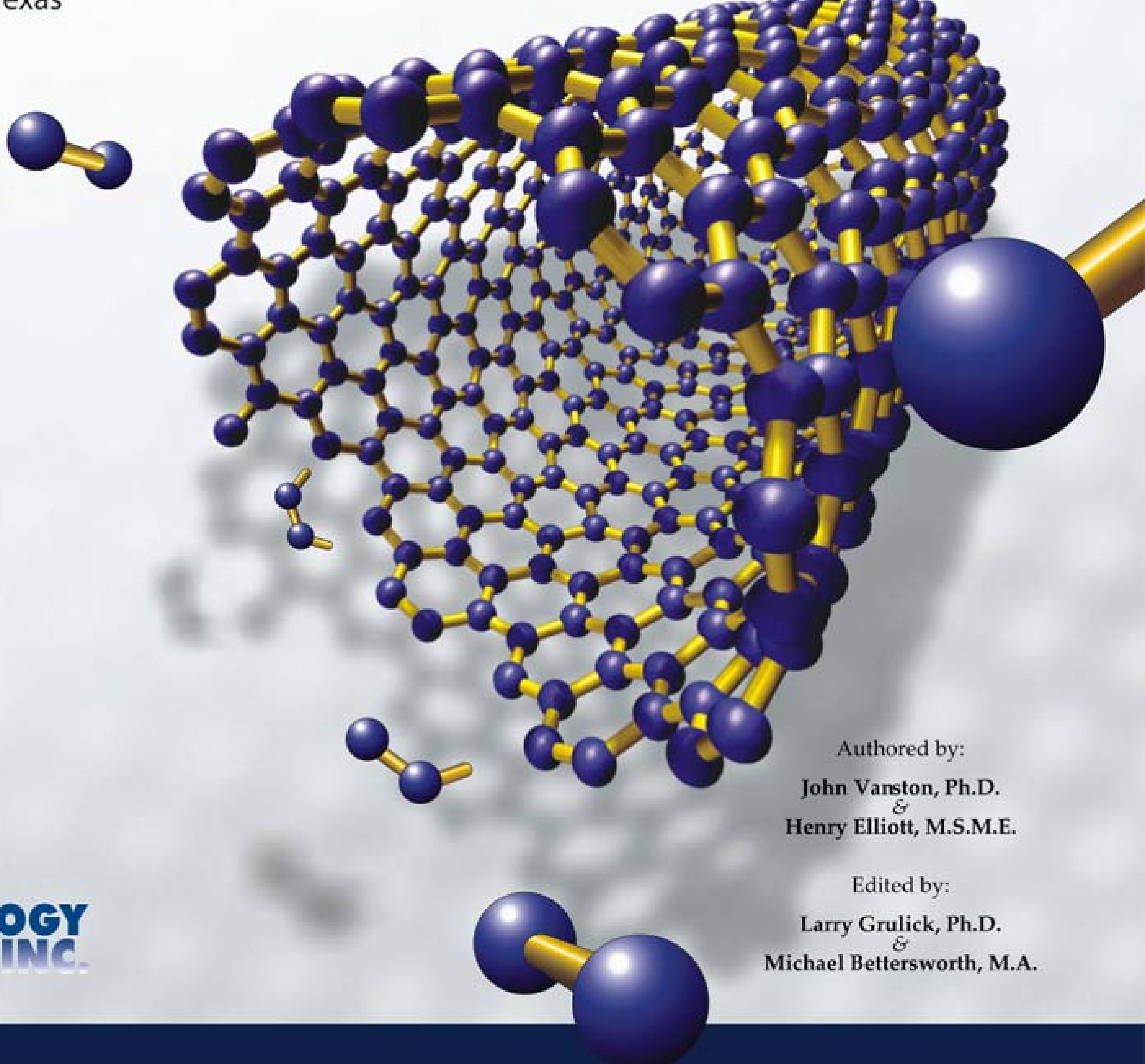
Nanotechnology
A Technology Forecast

Implications for Community & Technical Colleges in the State of Texas



Authored by:
John Vanston, Ph.D.
&
Henry Elliott, M.S.M.E.

Edited by:
Larry Grulick, Ph.D.
&
Michael Bettersworth, M.A.

TECHNOLOGY FUTURES INC.

Texas State Technical College

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Authored by:

John Vanston, Ph.D.
&
Henry Elliott, M.S.M.E.

Program Directors:

Michael Bettersworth, M.A.
&
Larry Grulick, Ph.D.

Texas State Technical College
3801 Campus Drive
Waco, Texas 76705
Main: 254.867.3995
Fax: 254.867.3393
www.tstc.edu

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Table of Contents

Preface

The research presented in this report is designed to provide Texas community and technical college instructional officers and curriculum development coordinators/directors with timely analysis and actionable insights into emerging technologies and their potential impact on existing and new technical educational curriculum. A highly skilled workforce is essential to the success of Texas companies and the overall economic competitiveness of the state. Therefore, by anticipating and proactively responding to future Texas workforce demands, community and technical college curriculum offerings can be a constructive force in attracting high-tech companies to the state and ensuring existing high-tech companies continue to have an appropriately skilled source of employees. This research hopes to drive the development and support of emerging technology curriculum and facilitate informed and accurate future curriculum development efforts for all Texas community and technical colleges. Texas State Technical College has contracted with Technology Futures, Inc. (TFI) to conduct this technology forecast on nanotechnology. The plans for this technology forecast were submitted to TSTC on November 20, 2002, and this report presents the results of this technology forecast and its implications for the state's community and technical colleges. Although this report is targeted towards these institutions, the information and insights presented herein may well be of interest and value to other individuals and groups.

Acknowledgments

Any reasonably comprehensive technology forecast is founded on the efforts of not one or two people, but rather on a number of recognized experts. Because of the broad range of technologies included in the term "nanotechnology" and because of the rapid development and expansion of the field, this is especially true for a technology forecast such as this one.

One of the most interesting activities in developing this forecast was a meeting to identify trends, events, and decisions that might either accelerate or deter the development of a vibrant nanotechnology industry in Texas. The value of this meeting was founded on the knowledge, experience, and insight of the participants. The authors sincerely appreciate these experts taking the time and effort to participate in this meeting. These participants included:

- ***Dr. Kevin Ausman***, Executive Director, Center for Biological & Environmental Nanotechnology, *Rice University*
- ***Dr. Richard Fink***, Vice President, *Applied Nanotech, Inc.*
- ***Dr. Denny Hamill***, Vice President, Business Development, *Nanotechnologies, Inc.*
- ***Kelly K. Kordzik***, Shareholder, *Winstead Sechrest & Minick*
- ***Christopher Shonk***, Partner, *Gendeavor Consulting Group*
- ***David Smith***, Vice President, *Technology Futures, Inc.*
- ***Dr. Robert Wenz***, Associate Director, *University of Texas at Austin Center for Nano & Molecular Science & Technology*
- ***Dr. Dennis Wilson***, Chief Technology Officer, *Nanotechnologies, Inc.*
- ***Dr. Zvi Yaniv***, President & CEO, *Applied Nanotech, Inc.*

We would like to also thank Dr. Hamill and Dr. Fink, as well as Conrad Masterson, CEO, *Nanotechnology Foundation of Texas*, who graciously agreed to review the final draft of the report and made very useful comments.

Listed in the "Experts Consulted" paragraph of the *Forecast Methologies* section of this report are 25 experts who were consulted by the authors during the development of this forecast. Each of these experts provided important information, opinions, and insights that were of major value, and we would like to thank each of them for their courtesy, patience, and willingness to contribute to the project.

This research was made possible by a Carl D. Perkins grant through the Texas Higher Education Coordinating Board. *Texas State Technical College* would like to thank the *Texas Leadership Consortium for Curriculum Development* and its Steering Committee members for their guidance and support for this and future technology forecast reports.

Finally, the authors would like to thank Debra Robison, Administrative Director, *Technology Futures, Inc.*, Eliska Beaty, Associate Vice Chancellor for Marketing & Communications, *Texas State Technical College System*, Jan Osburn, Director of Marketing & Communications, *Texas State Technical College Waco*, Mark Burdine, Coordinator of Photography, *Texas State Technical College Waco*, Mark Davis, Instructor, Digital Media Design, *Texas State Technical College Waco*, Bill Evridge, Director of Printing Production, *Texas State Technical College Waco*, and Debbie Moore, Prepress Technician I, Printing Production, *Texas State Technical College Waco,* for their outstandingefforts in editing, formatting, and printing this report. A special thanks is extended to Dr. Barbara Selke-Kern, Executive Vice Chancellor, *Texas State Technical College System*, for her guidance and final copy editing.

The primary foundation of this technology forecast is the input that we have received from the listed nanotechnology experts. The forecast reflects the authors' interpretations of these inputs. Any misinterpretations of these inputs are the fault of the authors, and we apologize for these to the people who have so obligingly contributed to our efforts.

Dr. John H. Vanston *and* ***Henry Elliott***

General Observations: Promising Potential

- The various areas of nanotechnology provide extremely promising commercial potential. However, the time required to achieve this potential is not clearly defined and varies between the different areas.
- Texas community and technical colleges should give serious consideration to conducting educational programs in nanotechnology. Because of uncertainties in the field, these programs should be founded on more basic skills that will allow employment in related fields. Emergence of the various nanotechnologies may well impact existing programs as well. For example, advances in the Electronics/ information areas may impact current Semiconductor Manufacturing programs. These issues are currently being addressed by the Texas Nanotechnology Curriculum Consortium.
- Although the specific skills, knowledge, and aptitudes that will be required of technical personnel involved in nanotechnology are not completely defined at this time, it is envisioned that they will be very demanding, and, thus, salary levels will be higher than those for most current technical jobs.
- There appears to be a sequence in which the different areas of nanotechnology will become commercially significant. In many of the nanotechnology areas, understanding of scientific principles has advanced to the point where greater research and development is being placed on the development of commercial products. Analysis of the development sequence for each area should give Texas technical and community colleges guidance for developing effective programs in these areas.
- The existence of technical and community programs in nanotechnology will serve as an incentive for attracting nanotechnology investment and commercial development in Texas.
- Although there is considerable interest in nanotechnology in Texas, this interest is currently overshadowed by interest in other states and countries. For example, state funding per capita for nanotech projects in New York and California are approximately two hundred times as large as funding in Texas.
- If Texas is to play a major role in nanotechnology, it will be essential for the state government, the nanotechnology consortia, the nanotechnology industry, and the state's academic community to clearly define goals and actionable objectives that will define Texas' leadership position in the field.
- So far, there has been little consideration given to the safety and environmental aspects of nanotechnology. Research and development in these areas should parallel research and development in product and process areas, or very unpleasant surprises may arise.
- The very unique characteristics of nanotechnologies may well present unique and largely unpredicted legal challenges. For example, potential liability issues may limit the use of nanotechnology materials in medical treatment. However, it is generally accepted in legal circles that current laws can deal with initial challenges and will probably have the flexibility to adapt to future requirements.

Nanotechnology: Workforce Issues

Today, there is scarcely any subject that elicits more interest and excitement in the science/engineering community, the business community, and the knowledgeable general public than nanotechnology. Current or projected applications range from more sanitary toilet seats to improved treatments for cancer. The information presented in the "Projections of Organizations" paragraphs of the "Nanotechnology Forecasts" section of this report indicates that nanotechnologies promise dramatic opportunities for our country and the world.

For example, the National Science Foundation projects that nanotechnology will become "a trillion dollar industry" by 2015. Moreover, the information presented in the "Current Texas Nanotechnology Activities" section verifies that there is a great deal of nanotech activity currently underway in the State of Texas.

However, translating the potential of nanotechnology into valid future employment analyses is a very uncertain matter. In this regard, it should be noted that current nanotech activities in the state involve primarily research activities at various universities and a group of small, entrepreneurial companies that range in size from one or two people to as many as 50 people. In university programs, most of the work typically done by technicians is done by students. Therefore, employment opportunities for people with associate degrees will depend primarily on the growth and success of current and

future small companies and, more importantly, the entry of large companies into the area.

At this time, the situation is characterized by a number of unknown factors, including what technologies will be successful, how rapidly the nanotechnology market will grow, how soon and in what manner large companies will enter the field, and what fraction of the nanotech industry will be located in Texas. Currently, the Nanotechnology Curriculum Consortium (see "Coordinating Groups") is conducting a survey of Texas companies to gather estimates of future employment possibilities. This survey should provide a clearer view of projected employment in the area.

There are many uncertainties involved in projecting future employment opportunities in the nanotech industry for people with associate degrees. However, there are a number of developments that will be useful to the state's community and technical colleges in their consideration of nanotech courses and programs. These developments include the following:

- Prospects for most of the state's current nanotech companies appear to be reasonably bright. In the past, much of the support for these companies has come from various grants, but several of these companies are now "selling products." At the recent *Nano Venture 2003* conference in Dallas, representatives of a number of venture capital firms (see Appendix A) indicated that they were looking for investments in promising nanotech companies. The representatives indicated that their firms were primarily interested in companies presently selling products or that had a clearly-defined market for their products. Moreover, the representatives indicated that venture capital firms had, in general, become more patient in considering returns on investments, e.g., accepting capital returns in about five years, rather than two years as was the pattern earlier.

- It is possible that the size of the nanotech industry in Texas could expand very rapidly in the near future. In a recent meeting, a group of nanotech experts were of the opinion that rapid growth would follow either the entry of one or more large companies into the field or the emergence of a highly successful nanotech company. Moreover, they indicated a belief that there was a real possibility of one or both of these events occurring in the reasonably near future, i.e., one to three years (see "Potential Impacting Factors" section). If either of these events should occur, there would be a strong demand for technically trained personnel in the nanotech field. The probability of these events occurring was highlighted by the May 2, 2003 announcement by Samsung Electronics Company, Ltd., that it planned to spend a half-billion dollars, over the next three years, to expand and upgrade its Austin, Texas semiconductor manufacturing facilities. The new facilities will be designed to produce silicon wafers with features 35% smaller than the 123 nanometer wafers currently being produced. Samsung projects that the new facilities will raise production from 35,000 to 45,000 per month and add about 300 people to its current payroll.

- Discussions with a number of nanotech companies in Texas and other states provide insights into some of the workforce realities in the area. The fraction of technician-level employees in these companies currently ranges from about 5% to about 30%. In many cases, tasks in these companies that would normally be done by technicians are currently being done by people with bachelor or higher-level degrees. This is partially because of the fact that, in small companies, everyone takes on tasks as they arise and partially because basic procedures and routines have not yet been established. Therefore, it is probable that the fraction of technicians in these companies will increase as the size of the companies increases. This probability was confirmed in interviews with executives in several companies. These executives stated that technicians were involved in production, maintenance, quality control, and administrative tasks. A key executive in one materials company estimated that the company would add four technicians for each $1,000,000 increase in sales.

- It is generally agreed by both business and academic professionals that technicians in nanotechnology will require more thorough grounding in scientific and technical areas than those in similar fields. Consequently, demand and pay scales will probably be higher than in other fields. Interviews with a number of company executives indicate that annual salaries for trained technicians will range from $30,000 to $50,000. In Appendix B, a list of probable job titles is presented, together with a description of routine and special skills required. For each job title, a range of probable hourly wages is shown, as well as a list of the nanotechnology areas requiring people with those skills.

The demand for community and technical college graduates will vary greatly among the various types of nanotechnology involved.

- The *instrumentation, tools, and computer simulation* fields probably offer the fewest employment opportunities for these graduates. The equipment involved is extremely expensive (often more than a million dollars), and the operation, calibration, and maintenance will normally be restricted to very highly trained and skilled individuals.

- The *nanomaterials* fields will probably offer the largest opportunities for graduates in the near future. To begin with, these are fields that are currently providing products for sale. Positions in which technicians can be utilized include production supervision, quality control, response to customer requests, equipment calibration and maintenance, and user education.

- In the *electronic/information and optical application* fields, near-term employment opportunities appear to limited. However, it is anticipated that these opportunities will expand as current research projects are translated into commercial products. In general terms, it is anticipated that employment opportunities will be similar to those currently offered by the semiconductor and computer industries.

- The *life sciences* fields will probably not offer much in the way of employment opportunities in the foreseeable future. Although the very promising potential of nanotechnology in medicine will undoubtedly motivate investment in this area, the high level of skills required for application will restrict employment of technicians. There will, of course, be a need for nurses, attendants, equipment repair people, and similar professionals. There may also be positions open to nanotech-trained technicians in the environmental area. These may include people trained in data gathering, processing, and analyzing; in equipment operation and repair; and in various administrative positions.

Employment possibilities in each of these fields are further discussed in "Imaging and Characterization;" "Commercial Opportunities for Nanoparticles", and "Commercial Opportunities for Bionanotechnology" in the "Nanotechnology: State of the Art" section.

Nanotechnology: Training Strategies for Community and Technical Colleges

Based on the factors listed in the preceding section, the following suggestions for evaluating, planning, and initiating nanotechnology courses and programs at community and technical colleges are offered:

- The current demand for people with associate degrees in nanotechnology is limited, but the requirements for such people could increase dramatically in the near future. Therefore, technical and community colleges should consider preparing programs, i.e., preparing curricula and training instructors, but not offering the programs until the demand for graduates and specific skills are more clearly defined.
- Colleges should coordinate their efforts in designing and initiating nanotech programs to maximize resource utilization.
- Nanotech programs should include strong foundations in scientific and technical areas such as chemistry, physics, materials, and electronics. Because of the importance of such a foundation, colleges may want to consider adding six months (Level II Certificates) or even a whole year (Advanced Technical Certificates) to their nanotech associate degree programs.
- Colleges offering nanotech programs should establish and maintain communication with local nanotech companies and consortia through advisory councils. Such organizations can provide advice, instructor support, instructional material, and, in some cases, equipment, as well as current or future employment opportunities.
- In most cases, colleges should base nanotech programs on currently available programs. For example, current programs, such as those for welders, medical technicians, electronics technicians, and electricians, could be modified by adding courses in nanotech subjects. Current programs could also be adjusted by substituting nanotech examples, problems, tests, and practical applications for those presently being used.
- Since many previous graduates will have a number of the skills required by the nanotech industry, colleges should consider offering skills upgrade or special topics courses for such people.
- Colleges considering the initiation of nanotech programs should maintain contact with the Nanotechnology Curriculum Consortium, www.westtexas.tstc.edu/nanotechnology/.
- Because the nature of nanotechnology is changing rapidly in terms of applications, understanding, business realities, required skills, and a host of other factors, it is highly desirable that executives and administrators in the state's community and technical colleges stay constantly aware of developments in the area. It may well be that colleges with little present interest in the area will find that changes in one or more of the listed factors may rapidly affect the attractiveness of nanotechnology to these colleges.

Nanotechnology: Current Texas Nanotechnology Activities

In his address to the Texas Technology Summit in Austin on October 9, 2002, Phillip J. Bond, U.S. Under Secretary of Commerce for Technology, commented that the State of Texas was "on the leading edge of nano research and nano business," and that "Texas is among a handful of states at the vanguard of nanoscience and technology, active in creating a world-class nanotech cluster of research institutions, private companies, business incubators, venture capitalists, and business organizations."

Indeed, there is a great deal of activity going on in the state in the nanotechnology area. Included in these activities are the formation of at least three different research consortia, seven university centers and institutes, and 16 companies.

Research Consortia

A number of privately-funded research consortia have been established to foster collaboration between academia and industry. One of the most prominent of these organizations is the Texas Nanotechnology Initiative (TNI) www.texasnano.org, which was founded in 1997 by Dr. Jim von Ehr (President and CEO of Zyvex) and Dr. Glenn Gaustad (a director at Zyvex). "TNI works closely with venture capitalists, academic institutions (consortia), and industry to foster relationships that advance Texas' position as a world leader in the discoveries, development, and commercialization of nanotechnology. TNI also lobbies Congress and state legislative bodies to pass laws that benefit the nanotechnology industry and to ensure that Texas organizations receive a fair portion of the funds allocated by the National Nanotechnology Initiative. TNI holds an annual venture conference, which consists of two full days of speakers and panels focusing on the current state of nanotechnology and related opportunities for investment."[1]

Another organization is the Nanotechnology Foundation of Texas (NFT) www.nanotechfoundation.org, whose CEO is Conrad Masterson. NFT is a "privately funded, not-for-profit organization that exists to assist current researchers in expanding their fields of investigation and to recruit highly-accomplished nanotechnology researchers to Texas from around the world. NFT provides this assistance by funding grants to research universities. NFT is planning to hold two events each year to promote nanotechnology research in Texas. The next event, planned for August 1, 2003, will be a "meet the researchers" program to introduce corporate research and development activities to the nanotechnology research programs and specialties at each university."[2]

Finally, the Corridor NanoBioTech Summit is a "unique forum for bringing together academic, economic development, government, and business leaders throughout the Greater Austin-San Antonio Corridor. The summit is designed to create a catalyst for the economic development of the corridor into a world-class technology center for research, development, and commercialization of new technologies resulting from the convergence of nanoscience with bioscience, biomedicine, and bioinformatics."[3] The first summit was held March 20, 2003. Major participants are The University of Texas at Austin, The University of Texas at San Antonio, The IC^2 Institute, The University of Texas Health Science Center-San Antonio, the Greater Austin Chamber of Commerce, and the Greater San Antonio Chamber of Commerce.

1 "Texas Nanotechnology Initiative." http://www.texasnano.org/about/default.htm
2 "Nanotechnology Foundation of Texas." http://www.nanotechfoundation.org/about.html
3 "Corridor NanoBioTech Summit." http://www.corridornanobiotech.org/

Universities and University Consortia

The long-term future for nanotechnology in Texas will be founded on the research institutions of the state. Currently, several universities have strong and expanding nanotech programs. For example, on October 1, 2000, The University of Texas at Austin committed $10 million to establish the Center for Nano and Molecular Science and Technology (CNM) www.cm.utexas.edu/cnm as one of the leading nanotech centers in the country. "The mission of the CNM is to foster education, science, and engineering in nanoscience and nanotechnology at The University of Texas. Research in the Center is presently focused in the following areas: bioelectronic materials, molecular nanoscale electronic materials, quantum dot and quantum wire nanoscale material, nanopatterning, and nano-imaging."[4] Within the CNM, there is a program in Integrated Nano Manufacturing Technology (INMT), "which will focus on new methods of nanomanufacturing. The goal of the INMT program is to learn how to manufacture nano products using low-cost processes that are environmentally friendly."[5]

At Rice University, Dr. Richard Smalley's Center for Nanoscale Science and Technology (CNST) www.cnst.rice.edu is a university-funded organization "devoted to nurturing science and technology at the nanometer scale. The 70,000-square-foot laboratory houses an interdisciplinary team of scientists and engineers who work on nanostructures, particularly carbon nanotubes. Their mission is to provide a venue where researchers from all disciplines of science and engineering can come together to share ideas and discuss their views and prospects of nanoscience, nanoengineering, and nanotechnology. CNST provides administrative support to the faculty and to joint projects and programs, supports joint research initiatives, performs fundraising, and sponsors seminars and conferences. CNST also encourages entrepreneurialism, encourages collaborations both internally and externally, connects to external organizations, and supports educational initiatives from "K to infinity" (i.e., from kindergarten to lifelong learning)."[6]

Also located at Rice is the Center for Biological and Environmental Nanotechnology (CBEN) www.rice.edu/cben, which is chartered to use nanotechnologies to improve human health and the environment. CBEN states that it "seeks to understand and ultimately manipulate artificial, chemically prepared nanobiosystems to better understand how nanomaterials impact complex, water-based systems of any size, from enzymes in a cell to global, environmental ecosystems. " The Center's location at Rice University allows it to tap into not only the university's world-leading expertise in fullerenes/carbon nanotubes, but also the resources of the nearby Texas Medical Center.

Another university involved in nanotech research is Texas A&M, which was named in June 2002 to lead the NASA University Research, Engineering, and Technology Institute (URETI). The URETI, called the Texas Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles www.tamu.ecu will advance nano-bio technologies that take form in "adaptive, intelligent, shape-controllable micro and macro structures for both advanced aircraft and advanced space systems."[7] The Institute includes researchers at Texas A&M, Prairie View A&M, Rice University, Texas Southern University, The University of Houston, and The University of Texas at Arlington.

4 "Center for Nano and Molecular Science." http://www.cm.utexas.edu/cnm/
5 Pastore, Michael. "Texas Program Hopes to Fuse Nano and Manufacturing." Nanoelectronics Planet (2002).
6 "Center for Nanoscale Science and Technology." http://cnst.rice.edu/cnst.cfm
7 "Texas Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles." http://tiims.tamu.edu/purpose.html

The University of Texas at Dallas has established a NanoTech Institute www.utdallas.edu/dept/chemistry/nanotech on its Richardson campus to conduct research in the field of nanotechnology. The Institute is headed by Dr. Ray Baughman, a globally recognized expert in the field. The chairman of the Institute's advisory board is Dr. Alan MacDiarmid, winner of the 2000 Nobel Prize in Chemistry. Dr. Jim Von Ehr, CEO of Zyvex, donated $2.5 million to the Institute.

The University of Texas at Arlington has established the Nanotechnology Research & Teaching Facility www.uta.edu/engineering/nano, which "provides faculty, students, and corporate engineers and scientists with the state-of-the-art equipment and interdisciplinary support needed to conduct investigations on and fabricate nanoscale materials, devices, electronics, and structures. Housed in its own building, the Facility features a 10,000-square-foot Class 1000 clean room that is divided into four areas of specialization: electron-beam and optical lithography, heterostructure growth and molecular beam epitaxy, solid state materials processing, and low temperature measurement."[8] The Facility, which has over $6 million in equipment, is headed by Dr. Wiley Kirk.

Moreover, the state's universities are cooperating to take fullest advantage of the special capabilities of each university. For example, The Universities of Texas at Austin, Dallas, and Arlington joined with Rice University in the spring of 2002 to form the Strategic Partnership for Research in Nanotechnology (SPRING). The leaders of SPRING obtained $6 million in federal funding in October 2002 to create an inter-institutional "virtual lab," which is expected to include "collaboration on research projects, coordination on programs and conferences, and development of joint facilities and infrastructure."[9] The organization will have a technical advisory committee that includes Nobel Laureate Richard Smalley (founding director of Rice University's Center for Nanoscale Science & Technology) and Paul Barbara (director of The University of Texas at Austin Center for Nano- and Molecular Science).

Finally, The University of Texas system campuse at Austin, Brownsville, Pan American, Arlington, and Dallas have established a nanotechnology consortium called "Nano at the Border", which seeks to introduce the field of nanotechnology to South Texas. "The goal of the initiative is to create an integrated, interdisciplinary education and research program in nanotechnology that allows participants on each campus to have the most advanced information about this field. The initiative will include classes and other means of information exchange as part of formal education programs and degree plans, development of faculty and student expertise, and enhanced outreach and commercialization."[10]

Among those taking an interest in the nano programs at the state's universities are large technology companies. Such companies see the universities as research and development research and development platforms from which they can both outsource some of their research and development and take advantage of the expertise in the field that has developed. For example, the Dow Chemical Company is licensing two new nanoparticle engineering technologies developed by a pair of University of Texas at Austin professors.

[8] "NanoFab Research and Teaching Facility." http://www.uta.edu/engineering/nano/
[9] "Strategic Partnership for Research in Nanotechnology" http://www.nati.net/m_eventsdetail.asp?eventid=402
[10] UT-Austin Press Release. http://www.utexas.edu/opa/news/03newsreleases/nr_200301/nr_nanotech030114.html

"The twin drug delivery powerhouses, called SFL (spray freezing into liquid) and EPAS (evaporative precipitation into aqueous solution), are separate processes for producing extremely fine, readily-absorbed (bioavailable) particles. SFL and EPAS both possess the ability to enhance a drug's performance by maximizing its particle surface area and wetability, thus making it more readily absorbed by the body."[11]

Coordinating Groups

To enhance coordination between the various nanotech activities in Texas, a number of coordinating groups have been established. These include the following:

Name	**Center for Biological and Environmental Nanotechnology, Rice University**
Contact	**Kevin Ausman, Executive Director**
Phone Number	**(713) 348-8210**
Nanotechnology Area	**Life Sciences**
Website	**http://www.ruf.rice.edu/~cben/**

Description: The Center for Biological and Environmental Nanotechnology is chartered to use nanotechnologies to improve human health and the environment. CBEN states that it "seeks to understand and ultimately manipulate artificial, chemically prepared nanobiosystems to better understand how nanomaterials impact complex, water-based systems of any size, from enzymes in a cell to global, environmental ecosystems." The Center's location at Rice allows it to tap into not only the university's world-leading expertise in fullerenes/carbon nanotubes, but also the resources of the nearby Texas Medical Center.

Name	**Center for Nanoscale Science and Technology**
Director	**Wade Adams**
Phone Number	**(713) 348-4890 (Rice)**
Nanotechnology Area	**All**

Description: The Center for Nanoscale Science and Technology at Rice University is a university-funded organization "devoted to nurturing science and technology at the nanometer scale. The 70,000-square-foot laboratory houses an interdisciplinary team of scientists and engineers who work on nanostructures, particularly carbon nanotubes. Construction began in 1997, making it a pioneering facility. It is equally devoted to the education of future scientists and engineers. The mission is to provide a venue where researchers from all disciplines of science and engineering can come together to share ideas and discuss their views and prospects for nanoscience, nanoengineering, and nanotechnology. CNST provides administrative support to the faculty and joint projects and programs, supports joint research initiatives, performs fundraising, sponsors seminars and conferences, encourages entrepreneurialism, encourages collaborations both internally and externally, connects to external organizations, and supports educational initiatives from "K to infinity" (i.e., kindergarten to lifelong learning)."[12]

[11] UT-Austin Press Release. http://www.utexas.edu/opa/news/02newsreleases/nr_200211/nr_dow021111.html
[12] "Center for Nanoscale Science and Technology." http://cnst.rice.edu/cnst.cfm

Name	**Nanotechnology Curriculum Consortium**
Director	**Bill Mays, Electronics Technology Instructor** **Texas State Technical College Sweetwater**
Phone Number	**(800) 592-8784, ext. 395**
Website	**http://www.westtexas.tstc.edu/nanotechnology/**
Nanotechnology Area	**All**

Description: Community and technical college instructional officers should pay particular attention to the Texas Nanotechnology Curriculum Consortium. Texas State Technical College West Texas, Sweetwater Campus is working with partner colleges throughout Texas "to pinpoint the specific workforce needs of the nanotechnology industry both statewide and across the nation." This project is in the process of identifying "the need for and type of comprehensive two-year training program and curricula required to position Texas-educated technicians on the ground floor of this fast-growing, advanced technology." Texas State Technical College has assumed fiscal agency and leadership of the project, in partnership with North Lake College and Richland College (Dallas County Community College District), Kingwood College (North Harris Montgomery County Community College District), Northwest Vista Community College (Alamo Community College District), and Austin Community College. Partner colleges were chosen because they expressed interest in the development of nanotechnology, they currently offer courses that can be integrated into nanotechnology programs, and their locations offer close proximity to industries currently investing in the new technology. It is believed that these shared attributes will enable all six partner colleges to incorporate a nanotechnology curriculum into their schools in the event the project proves a need for a two-year program.

Name	**The Corridor NanoBioTech**
Contact	**Jeff Webb, Greater Austin-San Antonio Corridor Council**
Phone Number	**(512) 245-2540**
Website	**http://www.corridornanobiotech.org**
Nanotechnology Area	**Life Sciences**

Description: The Corridor NanoBioTech Summit is a "unique forum for bringing together academic, economic development, government, and business leaders throughout the Greater Austin-San Antonio Corridor. The Summit is designed to create a catalyst for the economic development of the corridor into a world-class technology center for research, development, and commercialization of new technologies resulting from the convergence of nanoscience with bioscience, biomedicine, and bioinformatics."[13] The first summit was held March 20, 2003. Major participants are The University of Texas at Austin, The University of The Texas at San Antonio, The IC^2 Institute, The University of Texas Health Science Center-San Antonio, Greater Austin Chamber of Commerce, Greater San Antonio Chamber of Commerce, and the San Antonio-Austin Life Science. The IC^2 Institute has recently conducted a survey of nanotech activity in the Corridor area. The results of this survey are published in the report, *Catching the Next Wave in the Corridor*. Copies of this report can be obtained at The IC^2 Institute website www.ic2.org or by contacting Dr. Eliza Evans at (512) 482-0273.

[13] "Corridor NanoBioTech Summit." http://www.corridornanobiotech.org/

Name	**Nano at the Border**
Participant	**Dr. Juan Sanchez, Vice President for Research, University of Texas at Austin**
Phone Number	**(512) 471-0091**
Nanotechnology Area	**All**

Description: The University of Texas system campuses at Austin, Brownsville, Pan American, Arlington, and Dallas have established a nanotechnology consortium called "Nano at the Border", which seeks to introduce the field of nanotechnology to South Texas. "The goal of the initiative is to create an integrated, interdisciplinary education and research program in nanotechnology that allows participants on each campus to have the most advanced information about this field. The initiative will include classes and other means of information exchange as part of formal education programs and degree plans, development of faculty and student expertise, and enhanced outreach and commercialization."[14]

Name	**Strategic Partnership for Research in Nanotechnology (SPRING)**
Technical Advisory Committee Member	**Dr. Paul Barbara**
Phone Number	**(512) 471-2053 (UT Austin)**
Nanotechnology Area	**All**

Description: In April, officials from The University of Texas at Austin, Rice University, The University of Texas at Dallas, and The University of Texas at Arlington founded an organization known as the Strategic Partnership for Research in Nanotechnology, with the goal of ensuring Texas' role as a major player in nanotechnology. The coalition will collaborate on research, coordinate programs and conferences, and develop shared facilities.

Name	**The University of Texas at Dallas NanoTech Institute**
Contact	**Steve McGregor**
Phone Number	**(972) 883-2293**
Website	**http://www.utdallas.edu/dept/chemistry/nanotech/**
Nanotechnology Area	**All**

Description: University of Texas at Dallas has established The NanoTech Institute on its Richardson campus to conduct research in the field of nanotechnology. The Institute is headed by Dr. Ray Baughman, a globally-recognized expert in the field. The chairman of the Institute's advisory board is Dr. Alan MacDiarmid, winner of the 2000 Nobel Prize in Chemistry. Dr. Jim Von Ehr, president and CEO of Zyvex Corporation, donated $2.5 million to the Institute.

[14] UT-Austin Press Release. http://www.utexas.edu/opa/news/03newsreleases/nr_200301/nr_nanotech030114.html

Name	**The University of Texas at Arlington Nanotechnology Research and Teaching Facility**
Contact	**Dr. Wiley Kirk**
Phone Number	**(817) 272-5632**
Website	**http://www.uta.edu/engineering/nano/**
Nanotechnology Area	**Electronics**

Description: The Nanotechnology Research & Teaching Facility "provides faculty, students, and corporate engineers and scientists with the state-of-the-art equipment and interdisciplinary support needed to conduct investigations on and fabricate nanoscale materials, devices, electronics, and structures. Housed in its own building, the Facility features a 10,000-square-foot Class 1000 clean room that is divided into four areas of specialization: electron-beam and optical lithography, heterostructure growth and molecular beam epitaxy, solid state materials processing, and low-temperature measurement."[15] The facility, which has over $6 million in equipment, is headed by Dr. Wiley Kirk. Also involved in the research are the other member schools of the Metroplex Research Consortium on Electronic Devices and Materials at Southern Methodist University, Texas Christian University, University of North Texas, and The University of Texas at Dallas. The consortium was developed to conduct research supporting the electronics and telecommunications industries in the Dallas/Fort Worth area.

Name	**The University of Texas Center for Nano Manufacturing**
President/CTO	**Dr. Paul Barbara**
Phone Number	**(512) 471-2053**
Website	**http://www.cm.utexas.edu/cnm/**

Description: A new program in Integrated Nano Manufacturing Technology at the University of Texas will focus on new methods of nanomanufacturing. The program is an extension of the University's Center for Nano and Molecular Science and Technology. "The goal of the INMT program is to learn how to manufacture nano products using low-cost processes that are environmentally friendly."[16] Among those taking an interest in the nanomanufacturing program are large technology companies. Such companies see universities as an research and development platform. Universities allow companies to outsource some of their research and development, and it makes even more sense in nanotechnology because it allows industry to take advantage of the intense interest in nano that has taken hold at universities across the world.

[15] "NanoFab Research and Teaching Facility." http://www.uta.edu/engineering/nano/
[16] Pastore, Michael. "Texas Program Hopes to Fuse Nano and Manufacturing." Nanoelectronics Planet (2002).

Nanotech Companies in Texas

One of the most promising developments in the development of Texas nanotechnology has been the increasing number of small businesses that have been launched in the state. The attractiveness of Texas to nanotech industries is evidenced by the fact that two companies have moved to Texas from other locations–C Sixty, Inc. from Toronto, Canada to Houston, and Quantum Logic Devices from North Carolina's Research Triangle Park to Austin. Louis Brousseau, CEO of Quantum Logic Devices, says he moved to Austin to take advantage of the skilled workforce, academic community, and Austin's strong technology backbone. The next section provides information about nanotech companies in the state, together with descriptions of the products they currently offer or plan to offer in the near future.

Houston Companies

Company Name	**BuckyUSA**
CTO	**Dr. Felipe Chibante**
Phone Number	**(713) 777-6266**
Website	**http://www.flash.net/~buckyusa/**
Nanotechnology Area	**Materials (Fullerenes, Buckyballs)**

Description: BuckyUSA is a research and development company dedicated to the field of "fullerene science." The company has initiated a fundamental project targeting preparation and purification of fullerene products (pure fullerenes, chemically modified fullerenes, fullerene oxides), metal endohedrals, carbon nanotubes, and fullerene production/purification hardware.

Company Name	**C Sixty, Inc.**
President/CTO	**Dr. Robert J. Davis**
Phone Number	**(713) 626-5511**
Website	**http://www.csixty.com/**
Nanotechnology Area	**Life Sciences**

Description: "C Sixty is a private biopharmaceutical company focusing on the discovery and development of a new class of therapeutics based on the fullerene molecule, a hollow sphere made up of 60 carbon atoms that was discovered in 1985 as the third and unprecedented new form of elemental carbon in nature. It was dubbed buckminsterfullerene (or fullerene) because of its geodesic character.

C Sixty's major products are based on the modification of the fullerene molecule and include advanced products for the treatment of cancer, AIDS, and neurodegenerative diseases. The company is also committed to a research, development, and discovery program of novel biopharmaceuticals, diagnostics, and medical devices for applications in diverse disease categories based on the unique molecular pincushion platform of the fullerene molecule. The company has a diverse proprietary intellectual portfolio that includes five issued and three new patent applications."[17]

[17] "C Sixty Inc. Becomes Houston Technology Center Member Company" http://www.houstontech.org/en/articles/printview.asp?53

Company Name	**Carbon Nanotechnologies, Inc.**
CEO	**Dr. Bob Gower**
Phone Number	**(281) 492-5707**
Website	**http://www.cnanotech.com/**
Nanotechnology Area	**Materials (Carbon Nanotubes)**

Description: "CNI is a pioneer in carbon nanotechnology–single-wall carbon nanotubes, buckytubes, and related technology. The company was founded in 2000 and has an exclusive, worldwide license from Rice University for a broad array of technology developed by Professor Richard E. Smalley, a 1996 Nobel Laureate. The founders of the company include Dr. Smalley (who remains at Rice University), Dr. Bob Gower (former CEO of Lyondell Petrochemical), and Dr. Dan Colbert (former Executive Director of the Center for Nanoscale Science and Technology at Rice University and research collaborator with Dr. Smalley).

"CNI has an exclusive license for a broad array of technology developed over the last several years by Dr. Smalley. The existing patents and applications for patents cover intellectual property in several categories: process routes to produce buckytubes, buckytube derivatives, and technology for incorporating buckytubes into polymers."[18]

Company Name	**Molecular Electronics Corporation**
President/Chief	**Tim Belton**
Website	**http://www.molecularelectronics.com/**
Phone Number	**(843) 689-5699**
Nanotechnology Area	**Electronics (Molecular Self Assembly)**

Description: Molecular Electronics Corporation was co-founded by Rice University chemistry professor, Dr. James Tour. The company is "working to develop computer chips, memory circuits, and other electronic components that use nanoscale molecules in place of the microscale silicon transistors and switches in today's devices. The potential benefits of the molecular devices are enormous. For example, Dr. Tour believes that the volume of molecules needed to fill a drinking glass has the capacity to store about 1 trillion terabytes of data—about 1,000 times more information than humanity has accumulated in its entire existence—provided each molecule could retain one bit of information and be accordingly accessed."[19]

[18] "Carbon Nanotechnolgies Incorporated." http://www.cnanotech.com/pages/about/4-1_background.html
[19] Boyd, Jade. "Nanotech at Rice Promises Bright Future for Houston. *Rice News* Volume 11, Number 27 April 4, 2002

Company Name	**NanoSpectra BioSciences, Inc. (also Plasmonics)**
Founders	**Dr. Naomi Halas and Dr. Jennifer West**
Phone Number	**Halas (Campus), (713) 348-5611**
	West (Campus), (713) 348-5955
Website	**http://www.nanospectra.com/**
Nanotechnology Area	**Life Sciences (Drug Delivery, Tagging)**

Description: "Nanospectra Biosciences was formed in September 2001 to commercialize the life science applications of nanoshells. These nanoshells, a new class of materials, are tiny particles of silica that are covered with a thin coat of gold. They were invented by Dr. Naomi Halas and others at Rice University in the latter half of the 1990s. Dr. Jennifer West, Associate Professor of Bioengineering at Rice, co-developed the medical applications of nanoshells that led to the formation of the company.

"New forms of biomedical therapies, including cancer treatment, wound care, and diagnostic methods, are possible with gold nanoshells. Researchers at NanoSpectra have developed techniques to vary the thickness of the gold coating on the shells, which gives researchers the ability to "tune" the shells to be receptive to different wavelengths of light, particularly near-infrared light. By attaching proteins to the nanoshells, researchers can make the shells bind with specific types of cells, such as cancer cells in a tumor. After the nanoshells latch on to the tumor, near-infrared light—which has no effect on tissue itself—is projected into the patient's body, heating the shells and destroying the cancer. The technique has successfully destroyed tumors in lab mice, and the technology also is being adapted as a way to close wounds with heat."[20]

Company Name	**SES Research**
Phone Number	**(713) 686-9662**
Website	**http://www.sesres.com/index.asp**
Nanotechnology Area	**Materials (Fullerene/Nanotube Production Equipment)**

Description: "In 1990, only a handful of scientists were aware of the existence of fullerenes. The design of a new process for producing macroscopic quantities of these fullerenes led to a boom in the research of fullerenes. SES Research took this new process, refined and optimized the components, and manufactured one of the first fullerene production machines. The company now sells and designs these machines for interested parties."[21]

[20] Boyd, Jade. "Nanotech at Rice Promises Bright Future for Houston. *Rice News* Volume 11, Number 27 April 4, 2002
[21] "SES Research : Specialty Scientific Equipment Manufacturers" http://www.sesres.com/SpecialtyEquipManu.as

Dallas Companies

Company Name	**TissueGen**
Founder/Inventor	**Dr. Kevin Nelson**
Phone Number	(**817) 272-2540**
Nanotechnology Area	**Life Sciences (Tissue Repair)**

Description: "Using a patent-pending process for extruding biodegradable fibers implanted in damaged nerves with a mix of drugs, proteins, and growth factors, Dr. Nelson and his colleagues at the University of Texas at Arlington College of Engineering were able to bridge a 10-millimeter gap in the trunk of nerves running through the hind leg of a rat to restore movement in the rat's foot."[22] TissueGen has an office in the $1.5 million incubator on the campus of University of Texas at Arlington.

Company Name	**Zyvex**
CEO	**Dr. James von Ehr**
Phone Number	**(972) 235-7881**
Website	**http://www.zyvex.com/**
Nanotechnology Area	**Electronics/MEMS (Molecular Self Assembly)**

Description: Zyvex was the first molecular nanotechnology company. It was founded in 1997 by Dr. Jim Von Ehr, whose vision for the company was to make machines designed to build yet smaller machines that, in turn, build yet smaller machines that manipulated matter at the molecular level.

Over the past year, however, Von Ehr has been shifting the company's focus from the more distant possibilities of molecular manufacturing to the practical realities of cash flow. Zyvex is now selling the hardware and software it has developed to others in the MEMS (micro-electromechanical systems) and nanotech fields. Tom Cellucci, Chief Marketing Officer of Zyvex, says that they intend to market its nanomanipulators as the company's "first family of products." The company is also intending to generate revenue by licensing its intellectual property (IP) on carbon nanotube processing, a field in which it already has a number of patents pending.

[22] Wethe, David and Whiteley, Michael. "Tech incubator aims to bridge the nano-gap" *Dallas Business Journal* November 1, 2002

Austin Companies

Company Name	**Applied Nanotech**
CEO	**Dr. Zvi Yaniv**
Phone Number	**(512) 339-5020**
Website	**http://www.sidiamond.com/ani/**
Nanotechnology Area	**Materials (Carbon Nanotubes, Silicon Nanocrystals)**

Description: "Applied Nanotech is a research and development company dedicated to developing applications for nanoparticles such as carbon nanotubes, metalized dielectrics, silicon nanocrystals, and others, such as: carbon nanotubes as replacements for electron emitters for CRTs; cold cathode electron sources for low resolution; very high brightness (sun-visible) picture element tubes for electronic billboards; etc. The company is also developing silicon quantum dots."[23]

Company Name	**Dow Chemical Company**
President/CTO	**Technology licensed from The University of Texas Professors Dr. Keith Johnston and Dr. Bill Williams**
Phone Number	**Dr. Johnston, (512) 471-4617**
Nanotechnology Area	**Life Sciences (Drug Delivery)**

Description: Unfortunately, about one-third of new pharmaceutical drugs show poor solubility characteristics. "Every year, pharmaceutical companies give up on these promising but poorly soluble pharmaceutical because they have low bioavailability in the bloodstream and existing solubilization technologies cannot solve the problem. However, two new alternatives for solubilization developed at the University of Texas at Austin, and licensed by Dow, can help pharmaceutical companies bring more new drugs to market, giving doctors and patients more treatment options. The pair of drug delivery technologies, SFL and EPAS, are separate processes for producing extremely fine, readily-absorbed (bioavailable) particles."[24]

Company Name	**InnovaLight**
CTO	**Dr. Brian Korgel**
Phone Number	**(512) 471-5633**
Website	**http://www.innovalight.com**
Nanotechnology Area	**Materials (Quantum Dots, Luminescent Nanoparticles)**

Description: "InnovaLight is a seed-stage, venture-backed start-up focused on developing products around its novel, luminescent nanoparticles. The particles, produced via a wet chemical synthesis developed by Dr. Brian Korgel in the Chemical Engineering Department at University of Texas at Austin, have applications in CRTs and flat screen displays. The company, founded this year, has raised a round of funding from four prominent local venture capital firms and has received two government research grants."[25]

[23] "Company Profile." http://jmdutton.com/Research/SIDT/Profile/SIDT_Profile_Right.html
[24] UT-Austin Press Release. http://www.utexas.edu/opa/news/02newsreleases/nr_200211/nr_dow021111.html
[25] "InnovaLight, Inc." http://jobs.phds.org/jobs/position.cfm?EmployerID=934&CFID=477642&CFTOKEN=91490939

Company Name	**Molecular Imprints**
CEO	**Dr. Norman E. Schumaker**
Phone Number	**(512) 339-7760**
Website	**http://www.molecularimprints.com/**
Nanotechnology Area	**Electronics (Imprint Lithography)**

Description: This company was founded in February 2001 to "design, develop, manufacture, and support imprint lithography systems for use by semiconductor device manufacturers."[26] Molecular Imprints has an exclusive license to develop and use S-FIL technology, which was invented at the University of Texas at Austin under the direction of Professors Grant Willson and S. V. Sreenivasan, for the lifetime of the patents. As of April 2002, the company has nine patents filed or granted. This lithography approach may be the enabling technology for research applications in the areas of nano-devices, MEMS, and optical communications components and devices.

Company Name	**Nanotechnologies, Inc.**
CTO	**Dr. Dennis Wilson**
Phone Number	**(512) 491-9500**
Website	**http://www.nanoscale.com/**
Nanotechnology Area	**Materials (Metallic and Metal Oxide Nanoparticles)**

Description: Nanotechnologies, Inc., was founded in September 1999 to develop and commercialize a novel process for synthesizing nanopowders. The company's plasma-based, patent-protected technique produces non-agglomerated, dry metallic, and metal oxide nanoparticles in homogeneous gas phase suspension. The company is exploring the potential of the powders in a wide variety of application areas, including antimicrobial coatings, conductive adhesives for electronics, next-generation photovoltaic cells, and energetic materials.

Company Name	**Quantum Logic Devices**
President/CTO	**Dr. Louis C. Brousseau, III**
Phone Number	**(512) 302-5030**
Website	**http://www.quantumlogicdevices.com/**
Nanotechnology Area	**Electronics/Materials (Single Electron Transistors)**

Description: QLD is developing single-electron transistor platforms based on quantum dots that use very low power. QLD claims that its proprietary designs allow inexpensive fabrication and room temperature operation, which cannot be done with other approaches. They also claim that these "devices can also directly detect single molecular reactions electronically. This level of sensitivity is most useful for applications such as medical diagnostics, drug discovery, and bio/chemical warfare defense systems."[27]

[26] "Molecular Imprints." http://www.molecularimprints.com/AboutMII/AboutMII.html
[27] "Welcome to Quantum Logic Devices." http://www.quantumlogicdevices.com/index.htm

Company Name	**Teravicta Technologies**
President/CTO	**Dr. Robert Miracky**
Phone Number	**(512) 684-8700**
Website	**http://www.teravicta.com/**
Nanotechnology Area	**MEMS/NEMS**

Description: "Teravicta Technologies provides relay and radio frequency (RF) switch components and module solutions based on proprietary MEMS technology. Teravicta's initial product is an RF MEMS switch that combines ultra-low-loss, high-linearity, and low- power consumption in a miniaturized package. Applications for Teravicta's products include test instrumentation, cell phones, wireless LANs, fixed broadband wireless, cellular base stations, industrial control, satellites, military communications, and radar systems."[28]

Company Name:	**Winstead Sechrest & Minick P.C.**
Section Head Chair:	**Kelly K. Kordzik** **Nanotechnology Practice Group**
Phone Number:	**512.370.2851**
Website:	**www.winstead.com**
Nanotechnology Area:	**Legal**

Description: The Dallas law firm of Winstead Sechrest & Minick P.C. has launched a nanotechnology practice, one of the first of its kind in the nation. The practice will be a component of the firm's intellectual property and corporate sections, and will offer legal counseling on filing and prosecuting patent applications in the field of nanotechnology. Winstead has been providing nanotechnology support for several years. The firm supplied IP support related to nanotechnology to Rice University and Dr. Smalley, underwrote the Rice Alliance for Technology & Entrepreneurship, represented Austin's Applied Nanotech, and hosts a biweekly nanotechnology colloquium.

Company Name	**Xidex**
President/CTO	**Dr. Paul F. McClure**
Phone Number	**(512) 339-0608**
Website	**http://www.xidex.com**
Nanotechnology Area	**Instrumentation/Characterization (Atomic Force Microscopy, Magnetic Resonance Force Microscopy)**

Description: "Xidex is developing sensing and probing tools and studying carbon nanotubes. Dr. McClure is a former professor of mechanical engineering at University of Texas at Austin. The company has extensive experience in microscopy (atomic force microscopy and magnetic resonance force microscopy) for single proton imaging."[29]

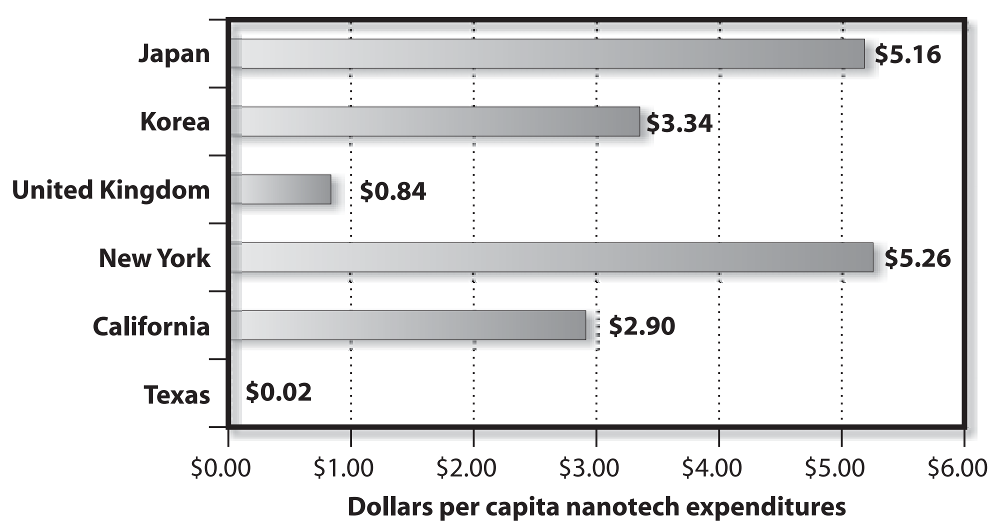
[28] "Teravicta Technologies: Frequently Asked Questions" http://www.teravicta.com/faq.php
[29] "Austin Embraces Small Tech." *Small Times Magazine Special Edition: Big Star in Small Tech* March/April 2002

Current Challenges

In his comments on the status of the nanotechnology industry in Texas, Secretary Bond stated that Texas is currently only behind California in nanotech development. However, it should be noted that this position may well be in jeopardy. This is reflected by the fact that current state funding dramatically lags that of other states and countries. Shown in Exhibit 1 is the current spending per person by different government entities (see also Appendix C).

In order to maintain a major position in the nanotech field, the Texas Nanotechnology Initiative is preparing a position paper for the current state Legislature encouraging strong state investment in the area. However, given the current state budget situation, significant funding appears doubtful. It should be noted that a similar situation occurred with regard to the Southeast Bio-Technology Park. Supporters envisioned this massive $633 million project to be located near the Texas Medical Center and to employ thousands of people over the next decade. The park was to be located on land that was mostly owned by the The University of Texas System, and supporters asked the state Legislature for a grant of $20 million for infrastructure improvements. The Legislature approved the $20 million, but as a loan rather than a grant. This difference materially changed the economics of the project and a much less ambitious project is now being planned.

Exhibit 1
Comparative Per Capita Nanotechnology Spending



Sources: Central Intelligence Agency *World Fact Book*,
National Science Foundation, state government websites, and Michael Porter.
Information compiled and analyzed by Conrad Masterson of the Texas Nanotechnology Foundation.

Data are generally for 1999 except for Nano Funding, which are 2001 data for states and 2002 data for foreign governments.

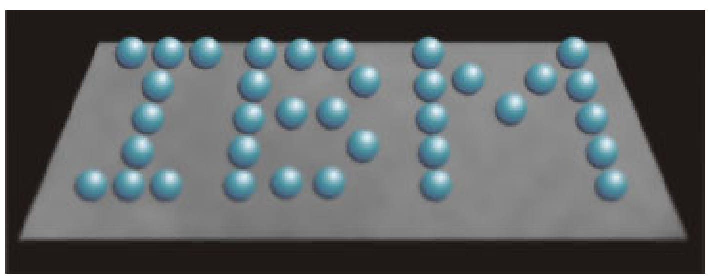
Instrumentation, Tools, and Computer Simulation

The 1993 National Science Foundation (NSF) panel report, *Atomic Imaging and Manipulation (AIM) for Advanced Materials* (NSF 93-73), concluded that important scientific discoveries would be made possible only with the continued development of more powerful and economical tools capable of imaging, characterizing, and manipulating structures with nanoscale dimensions.[30] This assessment is still true, and these tools are currently being used to assemble and measure the fundamental chemical, physical, and biological properties of various nanosized systems. "In the longer term, these tools will evolve into inexpensive, easy-to-use sensors and/or diagnostic devices with broad applications."[30]

Imaging and Characterization

Scanning probe microscopes (SPMs)–the scanning tunneling microscope (STM) and the atomic force microscope (AFM)–were developed at the IBM Zurich Laboratory in the 1980s. These instruments were crucial to the actual development of nanotechnology because they enabled observation of physical, chemical, and biological phenomena at nanometer scales (see Exhibit 2).[31]

Exhibit 2
Scanning Tunneling Microscope Image



IBM's Initials spelled out with 35 individual xenon atoms.
The image was produced with a scanning tunneling microscope.

Image courtesy of IBM Visualization Lab

The central element in each of these microscopes is a very fine needle or tip which is moved very close to the surface of a material. By measuring various physical forces, current (STM), and force (AFM), as the tip moves across the object, a fine scale image of the surface (topography) can be created. Although first-generation probe microscopes were limited to monitoring topography, "a broader class of scanning probes, derived from these initial instruments, have given researchers the ability to move atoms around and examine other local properties"[32], including:

[30,31,32] National Science and Technology Office Report, *Nanotechnology Research Directions: IWGN Workshop Report Vision for Nanotechnology Research and Development in the Next Decade*.

- ***Electronic structure*** "by scanning tunneling spectroscopy (STS), particularly at low temperatures."

- ***Optical properties*** "by near-field scanning optical microscopes (NSOMs). The NSOM beats the diffraction limit and allows optical access to sub-wavelength scales (50nm to 100nm) for elastic and inelastic optical scattering measurements, as well as for optical lithography."

- ***Temperature*** "by scanning thermal microscope (SThM). The SThM uses a temperature-sensing tip to map temperature fields of electronic/optoelectronic nano-devices and to measure thermophysical properties of nanostructures."

- ***Dielectric constants*** "by scanning capacitance microscopes (SCMs). Since the capacitance of a semiconductor depends on carrier concentration, the SCM enables the researcher to map out dopant profiles in semiconductor devices with nanometer- scale spatial resolution."

- ***Magnetism*** "by magnetic force and resonance microscopes (MFMs). The MFM can image magnetic domains and is already an integral part of characterizing magnetic storage media."

- ***Biological molecule folding/recognition*** "by nanomechanics. Single molecule nanomechanics measurements can provide insights into the molecular phenomena that dominate biological systems and have previously been probed only by measurement of ensemble averages."[33]

The largest manufacturer of SPMs, AFMs, and their accessories is Veeco (Woodbury, New York).

High-Resolution Electron Microscopy

Electron microscopy involves the examination of solid samples using scanning and transmission electron microscopy (SEM, TEM). An extremely powerful extension of this capability, high resolution electron microscopy (HREM), is an essential characterization tool for relating the morphology (sample shape), crystal structure, and quantitative elemental (compositional) analysis of solid nanomaterials to other material parameters including synthesis/processing, properties/performance, and theory/modeling. Hideo Onishi, a senior trade adviser with the Japan External Trade Organization (JETRO), indicated that a group at Hitachi led by Akira Tonomura has successfully developed the most powerful HREM in the world. The device is capable of imaging and distinguishing structures with dimensions on the scale of individual atoms.

The largest manufacturers of HREM devices are JEOL and Hitachi (Japan) and LEO (Germany).

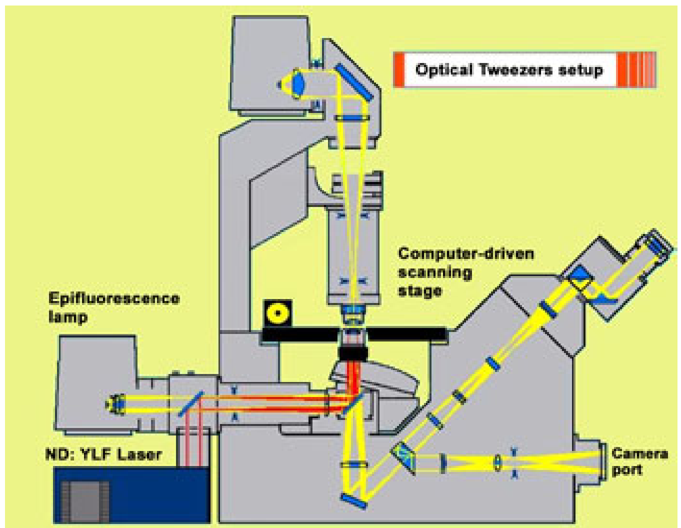
Manipulation of Nanostructures

Scientists are at a "fundamental limit for improving materials behavior through controlling composition and/or structure."[34] Any further improvements in material behavior will have to be made through the manipulation of structures at the nanoscale. There have been many important advances at nanoscale manipulation:

[33,34] National Science and Technology Office Report, *Nanotechnology Research Directions: IWGN Workshop Report Vision for Nanotechnology Research and Development in the Next Decade*

Optical tweezers provide a new approach to "gripping and moving nanometer structures in three dimensions."[35] The "tweezers" rely on the ability of strongly focused laser beams to "catch and hold particles (of dielectric material) in a size range from nanometers to microns."[36] This technique makes it possible to study and manipulate particles such as atoms and molecules.

Exhibit 3
Microscope-Based Optical Tweezers



Source: Professor Francesco Pampaloni
Department of Analytical Chemistry, Chemo- and Biosensors, University of Regensburg

Nanomanipulators will provide the means to build very precise structures that are assembled with "nanoscale" building blocks in three dimensions. Researchers have used them in SEMs and TEMs. In fact, Zyvex (Dallas) is currently marketing its newer high-performance nanomanipulators for SEMs. In Zyvex's idealized assembly process, a description of some object to be built is drawn in a computer-aided design (CAD) package. Computer-aided manufacturing (CAM) software decomposes the object into primitive building blocks and then into an assembly sequence. An assembler control computer uses this assembly sequence to control a huge number of nanomanipulators, each capable of moving a single molecular scale building block around at a time. The company is trying to develop applications in optical and radio frequency MEMS.

35 National Science and Technology Office Report, *Nanotechnology Research Directions: IWGN Workshop Report Vision fo Nanotechnology Research and Development in the Next Decade* (1999).
36 Arefin, Mohammad Lutful. "Optical Tweezers."http://www.uni-ulm.de/ilm/AdvancedMaterials/Presentation/Arefinopticaltweezers.pdf

Exhibit 4
Nanomanipulator Inside Scanning Electron Microscope

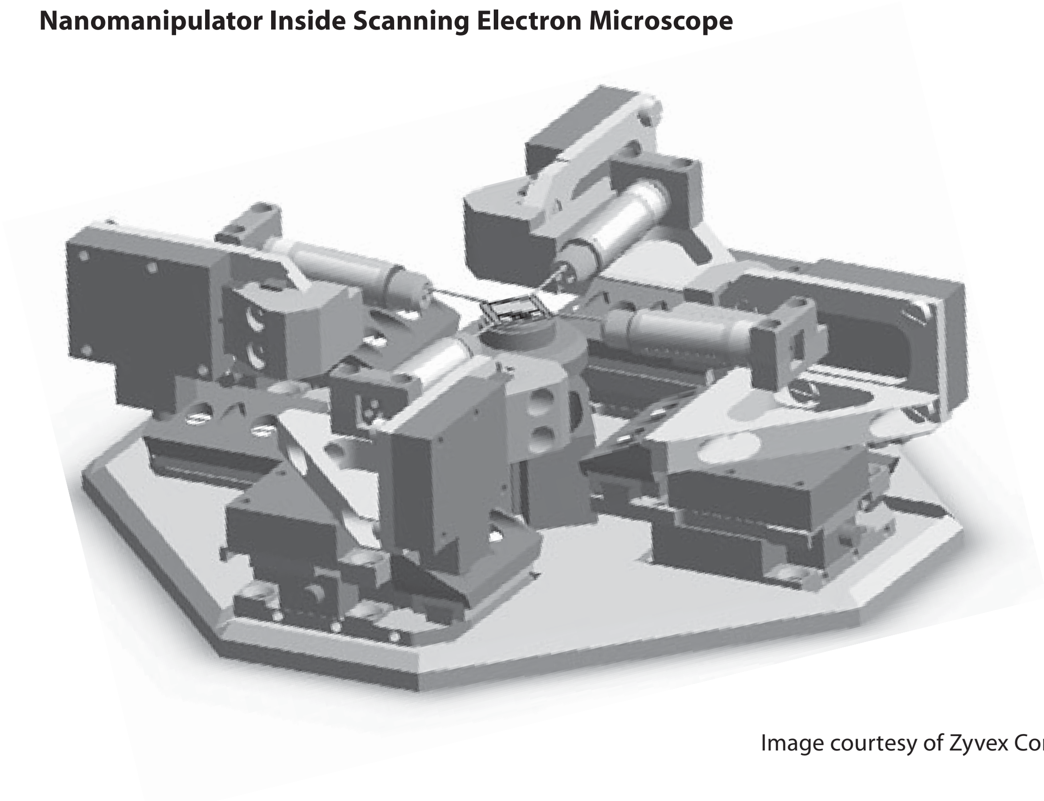


Image courtesy of Zyvex Corporation

Computer Modeling/Simulation

Computer modeling and simulation of complex phenomena is an important part of scientific investigation. In fact, since the early 1970s, materials development in the semiconductor and chemical industries has relied heavily on simulations, because direct observation is (a) difficult or impossible and/or (b) too expensive. Nanotechnology is quite similar in this respect, as it involves the understanding of physical and chemical properties at the "invisible" length scale of nano. Thus, computer modeling is extremely important, because it allows researchers to predict and observe behavior in nanostructures that they do not yet know how to measure or whose measurement requires very expensive measurement tools.

Nanomix (Emeryville, California) is a pioneer in this area. Nanomix has developed a set of "proprietary techniques that allows the synthesis of materials using computer simulations and, with a high degree of accuracy, predict their electronic, physical, and chemical properties. Its scientists can then synthesize, test, and discard useless or inferior materials virtually, selecting only those with the most potential for actual production in the physical laboratory. This approach represents a time- and cost-effective method of materials characterization and production."[37]

[37] "Nanomix Inc: Nanotechnology." http://www.nano.com

Training Opportunities for Imaging/Characterization/Modeling Tools

Many of the tools discussed above are already products today. However, most of them are produced in very small quantities and used exclusively by research laboratories. The demand for these tools, and the technicians to operate and service them, will increase as nanotechnology research spending increases. In fact, several technical colleges, including Texas State Technical College Harlingen and Austin Community College, already offer courses in microscopy in some of their surgical/biomedical technology curricula. Although graduates of these schools are not currently using microscopy equipment capable of characterizing nanostructures, they have somewhat of a head start on their peers due to their familiarity with the fundamental operations (specimen preparation, etc.).

It must be stated, however, that developing curricula using the most advanced of these nano characterizing instruments will be very difficult. The machinery is quite expensive to purchase and maintain, and trained instructors will be very hard to find. For example, the University of Texas at Austin uses a high-resolution JEOL 2010F electron microscope with a resolution of .5nm that costs close to a million dollars. Becoming proficient in all of the capabilities of the microscope requires operators with an extensive background in materials science and optics. This is true because the value in using the microscope is not in creating images but in *interpreting* the results in the image. In fact, even at a large research university such as the University of Texas at Austin, there are relatively few people qualified to use the device.

Materials

The importance of nanomaterials can be attributed to the fact that researchers realized the properties (electrical, optical, chemical, mechanical, magnetic, etc.) of nanoparticles can be selectively controlled by engineering the characteristics (size, size distribution, morphology, phase, and chemical composition) of the particles. These nanoparticles are referred to as *custom-engineered* nanoparticles. They are generally used for high-performance applications where the ability to control key characteristics is critical.

After developing custom-engineered nanoparticles in the near-atomic size range, engineers can incorporate them into other materials, exploiting the properties of the nanoparticles to create new combined materials with enhanced or entirely different properties from their parent materials. This incorporation takes many forms. For example, it may be a *coating* to alter surface properties, *nanocomposite* to alter bulk properties, *nanopowder mixture* or laminate for selectively altering bulk properties, or a delivery agent for pharmaceutical or biological applications.

Much of the hype surrounding nanotechnology has been centered on nanobots and molecular machines. It is possible that one day this vision will result in real products, but that is likely to be at least decades away. Nanoparticles are the branch of nanotechnology that can be put into products today. A number of Texas companies are developing such materials:

- ***Austin* –** Nanotechnologies, Inc., Applied Nanotech, and InnovaLight.
- ***Houston* –** Carbon Nanotechnologies, BuckyUSA, Nanospectra, C Sixty, and SES Research.

Opportunities for immediate application of nanoparticles fall into three categories: applications that *extend* current capabilities, applications that *improve* product performance, and applications that *revolutionize* products by creating new possibilities.

Extend

Nanoparticles can often be used as simple replacements for large powders to allow the same job to be done at a smaller scale. Examples include:

- Electrically conductive inks containing smaller conductive powders (silver) allow much finer electronic circuit lines.
- Spray coatings can be applied in thinner layers and with smaller grain size.
- Thermally and electrically conductive pastes containing powders can be applied more thinly, reducing conduction paths.

Improve

Smaller particles translate directly to improved performance, for example:

- Superior properties: greater hardness from the same material, transparency from normally opaque materials (aluminum oxide), reduced contact resistance, improved polishability.
- Easier processing: faster and lower temperature sintering and higher loadings in slurries and powder mixtures.

Revolutionize

Nanoparticles do things no other form of material can do, including:

- Novel properties: superparamagnetism (iron oxide), luminescence (quantum dots), and highly energetic materials (aluminum) for energy storage and propulsion.
- New possibilities: superplasticity, material combinations on the atomic scale, and quantum effects.

The applications and advantages listed here are not what will happen in a few years; they are happening now. Every day, rapidly growing companies develop new uses for nanoparticles, and successful products routinely appear on the market. Nanoparticles are still an emerging technology and vast potential remains, but the early movers are already reaping rewards.

Carbon Nanotubes

Because of the intense research interest they have generated and their centrality to the Texas nanotechnology community, a special class of nanoparticles, i.e., carbon nanotubes, is worthy of special note. Carbon nanotubes are cylindrical molecules approximately 1nm in diameter and 1-100 microns in length. They are composed of fullerenes, or "buckyballs," which are a relatively new form of carbon with 60 atoms perfectly linked into a soccer ball-like sphere. Rice University professors Dr. Richard Smalley and Dr. Robert Curl won a Nobel Prize in 1996 for this discovery.

Exhibit 5
Schematic Representation of a Carbon Nanotube

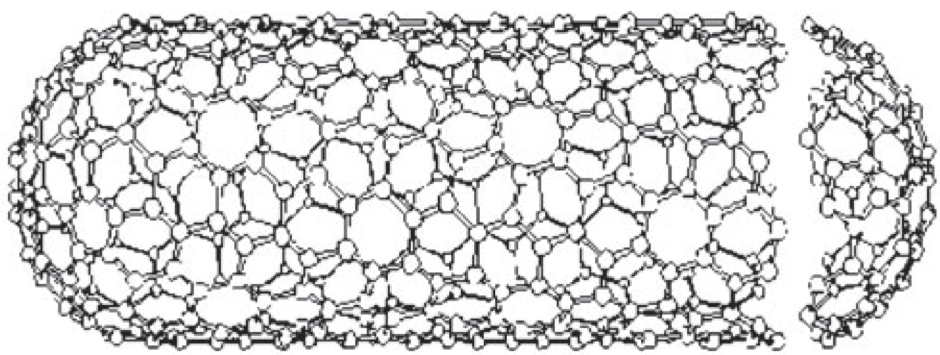


Image courtesy of Technology Futures, Inc.

The discovery of single-walled carbon nanotubes prompted a large interest in the electronic and mechanical properties of these novel materials. In theory, these nanotubes could be used to fabricate structural materials 500 times stronger than steel, but 10 times lighter. Additionally, nanotubes are non-toxic, conduct electricity better than copper at room temperature, and are better conductors of heat than diamond. Moreover, they have the ability to emit high-density electrons at very low voltages and fluoresce in the near-infrared spectrum. This quality makes them the world's best field-emitter, and their use in electron-based devices could make those items more effective and longer lasting.

The major hurdle to commercially realizing the potential of nanotubes has been the inability of researchers to produce uniformly-aligned, single-walled nanotubes with predictable properties. Therefore, it is not known how significant the discovery of fullerenes and nanotubes will turn out to be, but at least six companies in Texas are attempting to commercialize technologies built around them.

Commercial Opportunities for Nanoparticles

The difficulties in mastering the science and engineering to produce custom-engineered nanoparticles have meant that, in the past, these nanoparticles were unavailable except in limited research quantities. Now, however, custom-engineered nanoparticles for a broad range of applications are available. Applications for custom-engineered nanoparticles include:

Transparent coatings (aluminum oxide, niobia): Nanoparticles are significantly smaller than the wavelength of visible light, and, therefore, many materials can be made transparent by applying in a continuous coating. Nanoparticles, however, retain many of the physical properties they have as bulk materials, particularly hardness and wear resistance. This opens possibilities for extremely scratch/wear resistant transparent coatings for optics, optical fibers, and windows.

Structural composites (fullerenes, ceramic nanoparticles): Particulate reinforcement in composites has been long used to increase strength and stiffness of both polymers and metals. Nanoparticles can create even stronger, stiffer composites with additional properties, such as extremely low gas permeability.

Thermally/electrically conductive fillers (silver, copper, indium tin oxide, carbon nanotubes): Particle-filled adhesives for microelectronics are becoming increasingly important in heat transfer, as the power density of electronic devices continues to grow. Traditional particle fillers are reaching their limits as adhesive dimensions shrink. Nanoparticle fillers allow thinner adhesive layers and greater heat transport, and, therefore, more features in a smaller package.

Biologically active materials (silver, other noble metals): Because nanoparticles are on the same order of size as many biological structures, they can have much greater biological effects than the same material of larger size. Nanoparticles have been proven to be extremely effective in anti-infection bandages and as a biocide when mixed into polymers.

Biomedical applications (lanthanum carbonate, zirconium oxide, aluminum oxide): The human body presents a challenging environment for materials, an environment in which the properties of nanoparticles have a distinct advantage. For example, nanoparticles can be used to aid drug delivery or as structural materials in dental restoratives.

Catalysts (platinum, paladium, cerium oxide): The extremely high surface-area-to-mass ratio of nanoparticles makes them extremely effective catalysts. Nanoparticle-based catalysts can be used in lower amounts to provide for faster reactions than traditional, lower surface area catalysts.

Energetic materials (aluminum, boron): Although nanoparticles do not contain any more energy than larger size particles, the extremely small length scales involved mean that the energy can be released extremely quickly. This provides better propellants and improved explosives.

Direct write electronics (silver, copper): Several processes are being developed in the area of dip-pen "nanolithography," the printing of conducting lines on ever-increasingly complex circuits. Dip-pen nanolithography relies on having "ink" with appropriately sized nanoparticles.

Photovoltaics (titanium dioxide, niobia): Traditional solar cells have remained relatively expensive despite decades of development. Alternative designs based on the high surface area and photoactive nature of nanoparticles are already approaching the efficiency of traditional solar cells.

Electronics/Information Technologies and Optical Applications

Current integrated circuit (IC) manufacturing techniques utilize photolithographic techniques (light) to define circuit patterns. The major issue with photolithographic techniques is that, as circuit features shrink, the lenses required to define light at those dimensions become less reliable and more expensive to produce. In fact, the spatial resolution of conventional optical imaging instruments is limited by fundamental physical constraints to approximately 157 nanometers.

Thus, the continued validity of "Moore's Law," which states that the number of transistors on a microprocessor will double approximately every 18 months, could eventually come to an end unless radical changes in IC manufacturing technologies take place. Scientists hope that a number of technologies in development (including soft lithography, step-and-flash lithography, and molecular self-assembly) could fill the gap.

Additionally, as projected advances in computing take place, corresponding increases in memory and data storage capabilities will have to be achieved. Magneto-resistive random a ccess memory (MRAM), atomic resolution storage, single-electron tunneling devices, and high-density nonvolatile memory using carbon nanotubes (NRAM) are among the new technologies being developed.

Finally, micro-electromechanical systems will eventually shrink into nano-electromechanical systems (NEMS). Since MEMS devices require photolithographic manufacturing techniques, the new nanolithographic techniques described above will have to be in place before NEMS can become a reality.

Lithographic Techniques

Soft lithography: Instead of relying on light and optical equipment to create nanoscale circuit features, soft lithographic techniques rely on ordinary familiar printing techniques–printing, stamping, molding, and embossing.[35] The techniques are called soft lithography, because they all rely on a transparent, polymeric polydimethylsiloxane (PDMS) "stamp" with patterned relief on its surface to generate features.[38] "The stamps can be prepared by casting prepolymers against masters patterned by conventional lithographic techniques, as well as against other masters of interest."[39] With these techniques, researchers project that they will eventually be able to generate patterns with critical dimensions as small as 30nm.[36] Several different techniques are collectively known as soft lithography. Some of them are described below (see Exhibit 6):

[38] Whitesides, George and Love, J.C. "The Art of Building Small." *Scientific American* September 2001, p.43.
[39] Whitesides, George. "Soft Lithography." http://www.wtec.org/loyola/nano/US.Review/04_02.htm

Exhibit 6
Soft Lithography

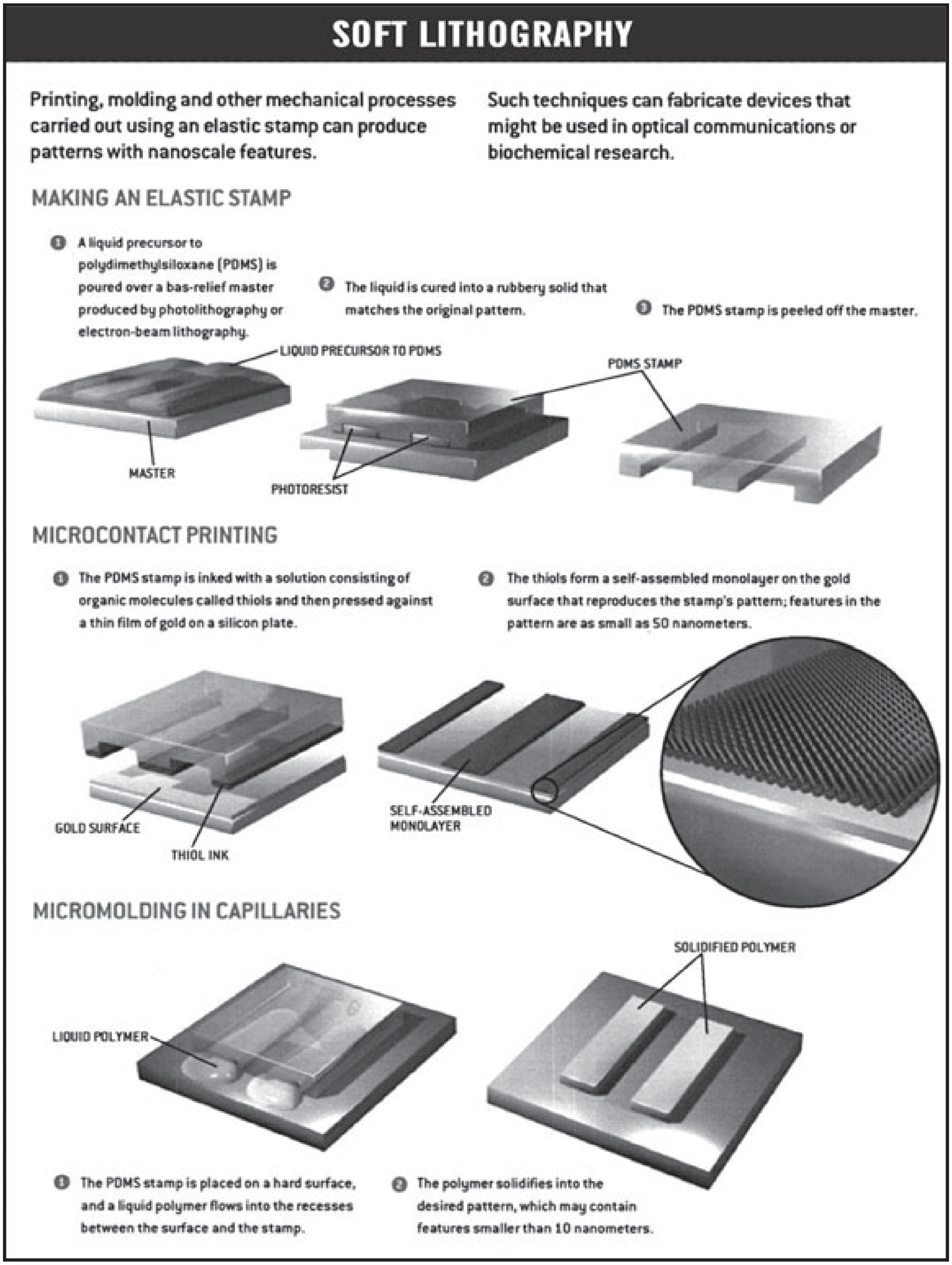


Image courtesy of Bryan Christie, www.bryanchristie.com

- ***Micromolding in capillaries (MIMIC):*** "Continuous channels are formed when a PDMS stamp is brought into conformal contact with a solid substrate. Capillary action fills the channels with a polymer precursor. The polymer is cured, and the stamp is removed. MIMIC is able to generate features down to 10nm in size."[40]

- ***Microcontact printing (MCP):*** "An ink of alkanethiols is spread on a patterned PDMS stamp. The stamp is then brought into contact with the substrate, which can range from coinage metals to oxide layers. The thiol ink is transferred to the substrate, where it forms a self-assembled monolayer that can act as a resist against etching. Features as small as 50nm have been made in this way."[41]

Unlike conventional photolithography, which must be carried out in a clean-room environment due to the sensitivity of the optical equipment to dust and oil, soft lithography is more tolerant. Thus, these techniques require modest capital investment and can be carried out in ordinary laboratory conditions at low cost.[42]

Step-and-flash imprint lithography: Another promising nanolithographic process in development is called step-and-flash imprint lithography. The technique, developed under the direction of University of Texas at Austin Professors C. Grant Willson and S. V. Sreenivasan, eliminates the need for a PDMS stamp. Instead, conventional photolithographic techniques are used to "etch a pattern into a quartz plate, yielding a rigid master. The master is then pressed against a thin film of UV-curable liquid polymer, which fills the master's recesses. The master is then exposed to light, which cures the polymer to create the desired replica."[42] The technology is being commercialized by Austin-based Molecular Imprints, Inc.

Memory and Storage

Current digital storage devices are approaching physical limits that will block additional capacity. Magneto-resistive random access memory (MRAM), atomic resolution storage, single-electron tunneling devices, and high-density nonvolatile memory using carbon nanotubes are among the technologies being developed to meet this challenge.

IBM has recently announced that it plans to introduce nanodrives–micro-mechanical devices with components in the nano-size range–within the next three years. This so-called Millipede drive will use "grids of tiny cantilevers to read, write, and erase data on polymeric media. The cantilever tips poke depressions into the plastic to make digital ones; the absence of a dent is a digital zero. The first Millipede products will most likely be postage stamp-sized memory cards for portable electronic devices."[43]

Additionally, there are already some start-up companies moving into the memory storage field. Nantero is growing carbon nanotubes on silicon to create high-density nonvolatile memory chips that could "store up to 10 times as much data as similarly sized regular RAM, while being faster and more power efficient."[44] Nanochip, Inc. is working on memory devices based on micro-electromechanical systems (MEMS)/atomic force microscope (AFM) storage.

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[40] Kim, E., Y. Xia, and G.M. Whitesides. "Polymer Microstructures formed by Moulding in Capillaries." *Nature. 376*: p. 581-584
[41] Kumar, A., and G.M. Whitesides. *App. Phys Lett.* 63:p. 2002-2004
[42] Whitesides, George and Love, J.C. "The Art of Building Small." *Scientific American* September 2001, p.43.
[43] Vettiger, Peter and Binnig, Gerd. "The Nanodrive Project: Millipede Project" *Scientific American* January 2003, p.48.
[44] Ewalt, David. "Nanotech Products will Arrive in Years, not Decades" *Information Week* May 13, 2002

Optoelectronics

Many groups are trying to develop a new class of optical components, called subwavelength optical elements, that increase the density, functionality, and integration levels of optical systems on chips.[45] The first commercial application for such devices will probably be optical switches used in micro-electromechanical systems (MEMS) and nano-electromechanical systems (NEMS) devices.

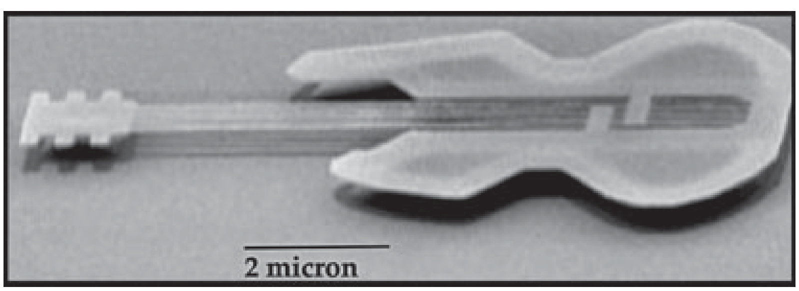
Molecular Self Assembly

In theory, "molecular self assembly is a strategy for nanofabricating circuits that involves designing molecules and supramolecular entities so that shape-complementarity (similar to that seen in biological structures such as DNA) causes them to aggregate into desired patterns. Self-assembly draws from the enormous wealth of examples in biology for inspiration and is one of the most important strategies used in biology for the development of complex, functional structures."[46] Although there is much hype surrounding the development of such structures, the authors believe that their realization is still many years away (if ever) and beyond the scope of this forecast

Nano-Electromechanical Systems

"NEMS is an extension of MEMS. NEMS and MEMS have great potential in the areas of biosensors, optical switches, micromirrors, routers, and quantum computers. The problem of heat removal is one of the major limitations in moving from the realm of MEMS to NEMS. Typical micro devices generate almost as much heat as is generated by a hot plate, while nano-devices generate heat approaching that of nuclear reactor or a rocket nozzle on a per-unit-volume basis. Fabrication of these devices will also be a major challenge. The new nanolithographic techniques currently under development will have to be perfected before fabrication of complex three-dimensional electronic and mechanical components will be feasible."[47]

Exhibit 7
The World's Smallest Guitar



The world's smallest guitar is 10 micrometers long–about the size of a single cell–with six strings each about 50 nanometers, or 100 atoms, wide. Made by Cornell University researchers from crystalline silicon, it demonstrates a new technology for a new generation of electro-mechanical devices.

Photo by D. Carr and H. Craighead [6]

[45] "nano opto." http://www.nanoopto.com/news/pr_4_16_02.html
[46] Whitesides, George. "Self Assembly and Nanotechnology." http://www.zyvex.com/nanotech/nano4/whitesidesAbstract.html
[47] "Nanotechnology: A Reality or Illusion." *Lokvani E- Magazine* http://www.lokvani.com/lokvani/article.php?article_id=602

Life Sciences

Perhaps no field of scientific inquiry stands to benefit more from advances in nanotechnology than biotechnology. In fact, as Paul Alivisatos, a UC-Berkeley chemistry professor and director of the new Lawrence Berkeley National Labs nanofabrication facility, has noted, all of biology is a form of nanotechnology, because even the most complicated organisms are constructed of cells made up of tiny nanosized "building blocks" (proteins, lipids, nucleic acids, etc.) that self-reproduce, regulate, and destroy. However, the challenge for scientists in this emerging field is to design and build *artificial* structures that can interact and, in some cases, mimic these very same biological structures to achieve desirable ends. It is projected that bio-nanotechnologists will use these artificial structures to develop new *biopharmaceuticals*, *diagnostic tools*, and *implantable biosensors and device*s.

Biopharmaceuticals

Drug delivery. "Every year, pharmaceutical companies give up on promising but poorly soluble pharmaceuticals, because they have low bioavailability in the bloodstream, and existing solubilization technologies are not adequate. To solve this problem, drug companies are developing new delivery systems that combine advanced nanomaterials with molecular manufacturing. These systems combine the advantages of high surface area, improved interfacial properties, and size confinement to deliver drugs that have increased efficacy, offer more convenient dosing regimens, and improved toxicity profiles over their micron-sized predecessors."[48] Two University of Texas professors (Dr. Keith Johnston, Chemical Engineering and Dr. Bill Williams, Pharmacy) are working with Dow to develop such systems.

Another nanoparticle-based delivery system is metal nanoshells, which were developed by Rice University professors, Dr. Naomi Hallas and Dr. Jennifer West. In theory, these nanoshells, which are being commercialized by a Houston-based company called Nanospectra, can be attached to antibodies that bind exclusively to cancerous cells. For cancer treatment, the shells would be introduced into a patient's body where they would attach to cancer cells. The shells, which capture energy at infrared wavelengths that can penetrate tissue, would then be heated by an infrared source. The heat would destroy the cancer cell.

Another possible targeted drug delivery system involves the use of nanomagnets that can be directed to specific sites within the body using external magnetic fields. These magnets would be attached to drugs that could treat specific cellular structures. The advantage of such a system is that it allows for very focused and intense treatment of diseased cells without harming cellular structures of non-interest.

New drug development. New "smart" drugs that can mimic natural disease-fighting cells in the human body are being investigated. In theory, these smart drugs would be capable of traveling through the body, "diagnosing" problems, and delivering "nano" doses of therapeutic medicine to diseased cells. This technology is very much in its infancy.

[48] UT-Austin Press Release. http://www.utexas.edu/opa/news/02newsreleases/nr_200211/nr_dow021111.html

Diagnostic Tools

Quantum dots. Quantum dots are nanoparticles with special luminescent properties useful in biologically "tagging" (identifying) cellular structures. Currently, to tag such cellular structures, organic fluorescent dyes are attached to molecules that have a natural tendency to bind with the structures. When the organic dyes are hit with light at a given wavelength, they fluoresce at a specific color, revealing the presence of a specific structure. In order to distinguish a number of different cellular structures, a number of different dyes, each with unique fluorescent properties, must be excited at different light wavelengths. Therefore, a multitude of cellular structures can be observed only by using a multitude of dyes, illuminated with lights of varying wavelengths, in a series of tests. However, the advantage of quantum dots over the current marker dyes is that their color can be altered by just varying their particle size. Thus, quantum dots offer the potential for multiple colors at one light wavelength, which increases the number of biological structures that can be tracked simultaneously.

Exhibit 8
Quantum Dots

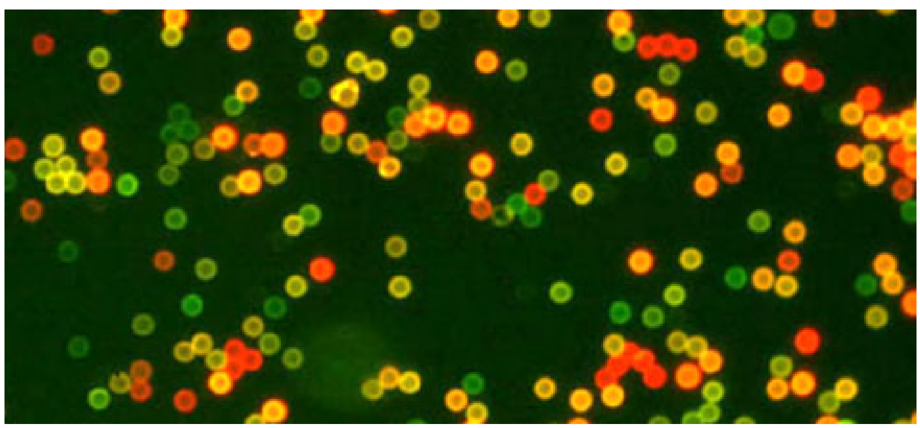


Image contains a total of 8 spectrally distinct quantum dots (nanocrystals).

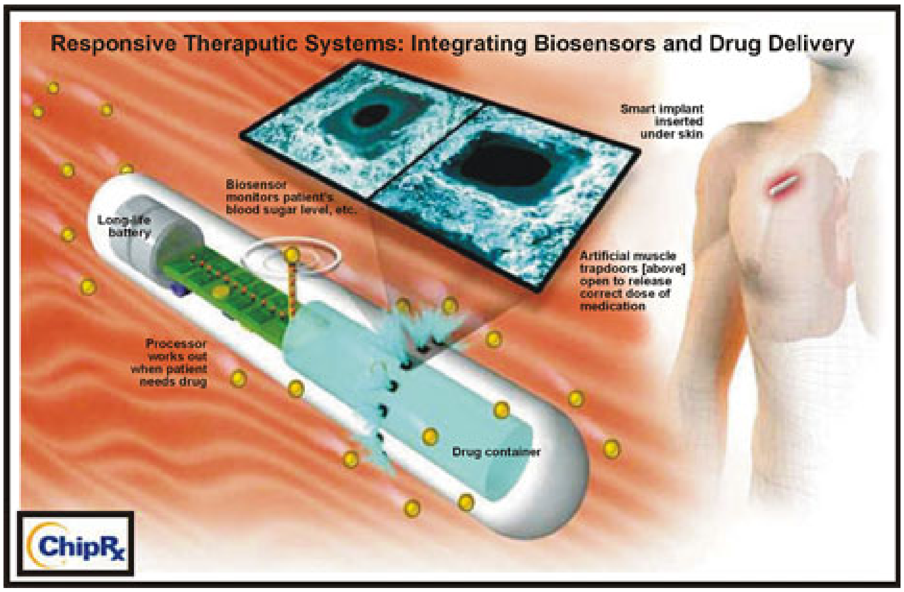
Image Courtesy of Quantum Dot Corporation

Additionally, about 12 million magnetic resonance imaging (MRI) procedures are conducted in the United States each year, and many benefit from the use of a contrast agent injected into the patient. These agents are vital tools for imaging, because they increase contrast between the target organ and surrounding tissues in the image, allowing for better diagnosis. The most common contrast agents are superparamagnetic nanoparticles (4nm to 6nm in diameter) based on gadolinium, manganese, or iron. These nanoparticles are called superparamagnetic, because they align relatively strongly when a magnetic field is applied but lose alignment quickly when the field is removed.

Lab on a chip. Nanomechanical devices could permit the construction of more economical DNA and protein screeners. In such devices, multiple strands of DNA material would be attached to a number of micron-sized cantilevers similar to the ones currently used in atomic force microscopes (AFMs). When genetic material with a complementary sequence bound itself to the DNA strands, the cantilevers would be deflected. Sensitive measurement equipment capable of capturing these deflections could be used in a system that rapidly identifies specific genetic sequences.

Exhibit 9

Responsive Therapeutic Systems



Responsive therapeutic systems: integrating biosensors and drug delivery.

Source: Professor Slyvia Daunerts[7]

Implantable Biosensors and Devices

Biosensors/devices. "Biosensors or chemical sensors, integrated and miniaturized, can be used to replace existing, more time-consuming analytical methods for monitoring and detecting physical phenomena."[49] For example, a nano-sized device could be implanted in patients with diabetes to constantly monitor blood sugar levels. This sensor would be connected to a nano device that would pump minute, precise levels of insulin into the patient. Such a device would help the patient maintain a safe blood sugar level and eliminate the need for patient self-diagnosis, which often leads to missed medications and incorrect/insufficient insulin doses that can have serious consequences. Other potential applications include blood flow monitors/pumps for heart patients and dialysis treatment for kidney patients.

[49] Walsh, Michael."Nano-and MEMS Technologies for Chemical Biosensors." ttp://www.atp.nist.gov/atp/focus/98wp-nan.htm

The ultimate success of these miniaturized devices, however, will depend on the ability of scientists to design inexpensive, reliable, and sensitive devices that exceed the specifications of the presently available technologies and can perform these tasks at the same or lower cost.[50]

Commercial Opportunities for Bionanotechnology

Currently, there are a number of companies, some of them Texas-based, that are developing commercial products and prototypes based on the technologies described above. In addition to Nanospectra and The University of Texas at Dow partnership, C Sixty (Houston) is using fullerenes as a scaffolding to build small molecule drugs. The company has two products in advanced preclinical stages for the treatment of HIV. However, from the perspective of Texas community and technical colleges, it is hard to project what kind of technical training would be required for employment in this field because these companies' products are still in the research and development and prototype development stages. At this point, interested parties should just keep abreast of new developments in the field.

[50] Walsh, Michael. "Nano-and MEMS Technologies for Chemical Biosensors."

Nanotechnology: Forecasts

Definition

Although there is widespread agreement that of nanotechnology promises dramatic advances in technological capabilities, as well as very attractive business opportunities, there is considerable disagreement, even among professionals in the field, as to what is meant by the term. The most generally accepted definition is that nanotechnology refers to any structure that is smaller than a hundred nanometers in at least one dimension. However, for this forecast, a definition similar to one presented by Dr. Zvi Yaniv, President and CEO of Applied Nanotech, is used. This definition includes the following elements:

- Nanotechnology involves the reduction in size of substances to the point where they display differences in one or more key parameters (optical properties, electrical or thermal conductivity, magnetism, and strength) when compared to the bulk or microscopic forms of the substances.
- It must be possible to organize, characterize, and manipulate these particles in a controlled manner.
- There must be at least a potential for commercial or socially desirable use of the technology.

For this forecast, one further element has been added:

- There must be a reasonable probability of practical use within the next five to eight years.

The authors believe that any project that does not promise practical use within that time period should be classified as "nanoscience."

It should be noted that "nanotechnology" is not a discipline, per se, but, rather, a large and diverse range of technologies (engineering, electronics, biotechnology, etc.) and scientific disciplines (materials science, natural sciences, life sciences). As such, it will have an impact on almost all established industries.

Classification

There are a number of ways that the various nanotechnology areas can be classified (see Appendix D).

- The Center for Nanoscale Science and Technology at Rice University classifies nanotechnologies into three categories: wet, dry, and computer simulation.
- Dr. Zvi Yaniv, President of Applied Nanotech, Inc., classifies nanotechnology into seven "pillars."
- Professor P. J. Ferriera of the University of Texas at Austin divides the area into six characterizations, notes six types of properties, and lists 11 applications.
- *Scientific American,* in its special Nanotech issue of September 2001, addressed the subject in 10 separate chapters.
- The National Nanotechnology Initiative funded six different Nanoscale Science and Engineering Centers, each focusing on specific nanotech areas.

- The Nanotechnology Foundation of Texas classifies nanotechnologies into seven commercial applications.

For this forecast, a classification system will be used that includes elements of all of these classification systems. These classifications will be as follows:

1 ***Instrumentation, tools, and computer simulation:*** The development of instrumentation and tools to provide, manipulate, measure, and visualize single atoms and molecules at the nanoscale is a prerequisite for further nanotechnology development. These tools include scanned probe microscopes, atomic force microscopes, scanning tunneling microscopes, transmission electron microscopes, and scanning electron microscopes.

2 ***Materials:*** The first nanoproducts to reach the marketplace, and the ones the authors have spent the most time researching, fall into the category of materials and materials manufacturing. Inorganic materials such as fullerenes, carbon nanotubes, and ceramic and metal nanopowders are being actively developed. The concept of creating "new" materials by incorporating nanosized filler materials into other materials has already been demonstrated with micron-sized particles used in currently available electronic adhesives, paints (pigments), and scratch resistant coatings. The new nanocomposite materials will have enhanced thermal, electrical, and mechanical properties.

3 ***Electronics/information technologies and optical applications:*** The continuation of Moore's Law in the semiconductor industry (permitting further miniaturization, speed, and power reduction in information processing devices) depends on the ability to create circuit features with nanoscale dimensions. Current circuit printing techniques using optical lithography become very difficult and expensive at these dimensions. New nanomanufacturing techniques, such as molecular self assembly and soft lithography, could be used to print more consistent and inexpensive circuit features. Additionally, as projected advances in computing take place, corresponding increases in memory and data storage capabilities will have to be achieved. Magneto-resistive random access memory, atomic resolution storage, single-electron tunneling devices, and high-density nonvolatile memory using carbon nanotubes are among the new technologies being developed. Finally, many groups are trying to develop a new class of optical components, called subwavelength optical elements, that increase the density, functionality, and integration levels of optical systems on chips.

4 ***Life sciences:*** No field of scientific inquiry stands to benefit more from advances in nanotechnology than biotechnology. For example, drug delivery technologies that increase drug efficacy provide for less inconvenient dosing regimens, and improved toxicity profiles are being developed. Furthermore, researchers are developing new diagnostic tools with increased sensitivity and efficiency using quantum dots (4nm to 5nm luminescent nanoparticles). In other work, researchers are developing nanomagnets that can be guided to exact sites in the body using external magnetic fields. This technology has potential applications in biomedical research, diagnostics, and drug delivery because materials of interest can be attached to the magnets and directed to precise areas in the body (to kill cancer cells, for example). Finally, others are developing implantable devices that allow for long-term drug release controlled by biosensors. Such devices could be implanted into patients to monitor and control critical biological processes. For example, a nanobiosensor implanted in a diabetic could measure the patient's blood sugar level and activate a nanopump that provides precise, constant injections of insulin into the bloodstream.

Forecast of Commercialization

Based on this categorization, the forecast of future developments in each category is presented in Exhibit 10.

Exhibit 10
Commercialization Realization Timeline

Modest Commercial Opportunity		
Short-Term (0-3 years)	Mid-Term (3-5 years)	Long-Term (5 or more years)
Instrumentation/Tools/ Computer Simulation	Instrumentation/Tools	Instrumentation/Tools
Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)	Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)	Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)
Important Commercial Opportunity		
Short-Term (0-3 years)	Mid-Term (3-5 years)	Long-Term (5 or more years)
N/A	Life Sciences (diagnostics)	Life Sciences (diagnostics, screening and tagging technologies)
N/A	Electronics/Information Technologies/Optical Devices	"Smart" Nanomaterials
N/A	Computer Simulation	N/A
Large Commercial Opportunity		
Short-Term (0-3 years)	Mid-Term (3-5 years)	Long-Term (5 or more years)
N/A	Life Sciences (drug delivery)	Life Sciences (drug delivery, drug design and development
N/A	Electronics/Information Technologies (data storage, microprocessors)	Electronics/Information Technologies/Optical (data storage, memory, optical devices, molecular and quantum computing) Nanoelectromechanical Systems (NEMS)

Source: Technology Futures, Inc.

Fundamental Driving Forces

Increased Interest

As a result of the dramatic promise of nanotechnology, there is a great deal of interest in the development of the technology. A number of large companies throughout the world, including IBM, Hewlett-Packard, Lucent Technologies, DeGussa, Mitsui, Hitachi, Samsung, and Phillips have invested, and are continuing to invest, a great deal of time, money, and effort in research and development in the area. Federal and state governments in the United States, as well as many foreign countries, are committing significant funds to industry development, and universities throughout the world, including many in Texas, are investigating various aspects of the technology. A simple indication of growing interest in the area is the growth over the last couple of years in patent applications and patents granted in nanotube technology (see Exhibit 11).

Exhibit 11
Nanotube Papers and Patent Applications

Year	Papers	Patent Applications
1999	70	50
2000	1,100	100
2001	1,500	200

Source: Edward T. Michalson, Winstead Sechrest & Minick

Research and Development Directions

Much of the research and development effort in nanotechnology has shifted from understanding the underlying scientific principles of nanoscience to developing products for practical application, including commercial products and services. The successful application and commercialization of nanotechnologies is a notable development and should be emphasized as these developments will undoubtedly impact KSAs (Knowledge, Skills, Abilities) for existing occupations and respective curricula and will likely produce entirely new workforce demands requiring new curriculum development.

Special Medical Interest

To a considerable degree, advances in technology, particularly in production technologies, will reflect increasing market demand. Generally, it can be expected that nanotech products that perform functions currently provided by other products will be adopted faster than nanotech products that perform new functions.

Since the public has an increased expectation in the area of healthcare, nanotech products and processes in the medical field will receive special attention and will progress faster than comparable products and processes in other areas. In the near future, the use of medical nanotech techniques can be expected when:

- Only small amounts are required.
- Expense is not a major factor.
- No other technique can be effectively utilized.

Legal Considerations

Because of the fact that many developments in nanotechnology will represent products and processes dramatically different from those available today, some new legal concepts may be required to adjudicate rights, responsibilities, and damages in this field. However, the general opinion in the legal profession appears to be that current laws and regulations are adequate for the near future and that new legal concepts and constructs can be formulated rapidly enough to meet emerging legal requirements in the field.

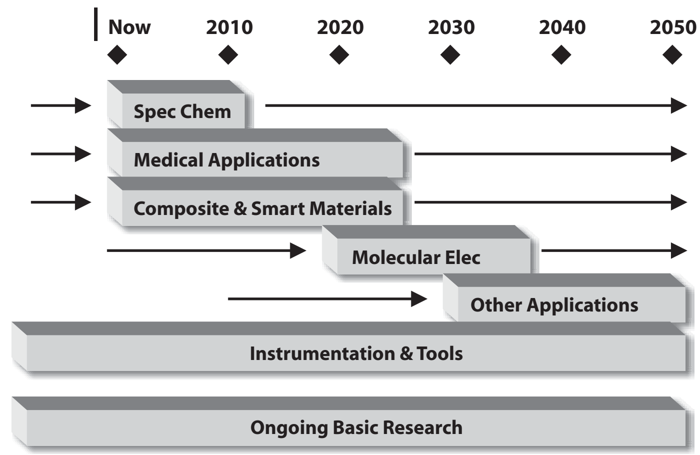
Projections of Organizations

A number of organizations have made dramatic projections about future growth of the nanotech industry in the United States and the world. Examples include:

- The National Science Foundation has projected that nanotechnology will become "a trillion dollar industry" by 2015 and the largest segment will be nanomaterials, which will reach $340 billion per year.[51]
- The Japan Federation of Economic Organizations reported that the Hitachi Research Institute estimated that the nanotechnology products market for Japan alone might be over $200 billion in 2010.
- The Texas Nanotechnology Initiative anticipates that approximately $1 billion will be invested in developing and applying nanotechnology in the State of Texas over the next five years.[52]
- The National Nanotechnology Initiative has provided multi-agency funding of $270 million in FY2000, $422M in FY2001, $604M in FY2002, and $774M in FY2003 to nanotechnology research. The proposed budget for FY2004 is $847 million.
- In 2001, the German VDI (Society of German Engineers) estimated the global market for nanotechnology products and processes at $54 billion.[53]
- Battelle Memorial Institute projects that nanotechnology will be one of the top three most important technologies of the 21st century.
- The Nanotechnology Foundation of Texas has projected the commercialization of different types of nanotechnology as shown in Exhibit 12. Although the classification system is a bit different from the one used in this forecast, the forecasts are similar, particularly in the shorter term, which is the main focus of this forecast.

[51] Official Statement by Mihail Roco, Senior Adviser for Nanotechnology, National Science Foundation
[52] Stuart, Candace. "Texas: Its Small Tech Machine Well Oiled." *Small Times Magazine* March 15, 2002
[53] "Capitol Stage Nanotech Invest." http://www.nanoinvestornews.com/modules.php?name=News&file=print&sid=440

Exhibit 12
Potential Development Timeline



Source: Texas Nanotechnology Foundation

- In *A Critical Investor's Guide to Nanotechnology*, In Realis, a venture capitalist investment advisory company, offers the advice shown in Exhibit 13. This advice well reflects the forecasts presented earlier in this document.

Exhibit 13
Nanotechnology Development Plans

Segment	Commercialization to Pursue	What to Avoid
Tools	Fundamental advances in nanoscale (or sub-nanoscale) techniques for visualization, measurement, and manipulation. Advances in process control.	Promises of very large near-term revenue opportunities. Competing on the basis of microscopy. Ignorance of potential entrants from semiconductor capital equipment markets.
Materials	Disruptive new material applications. Arbitrarily long nanotubes	Rapid growth expectations, high investment requirements. Yet another carbon nanotube or nanopowder company. Loose grips on scalability or application value.
Electronics	Disruptive new electronic applications of unique nanomaterial properties.	Sustaining developments in microprocessors other large, ordered arrays of transistors. Quantum computing.
Biotech	Tools to help with target identification and understanding disease mechanisms. New vehicles for drug delivery.	Undifferentiated new entrants into biotech field. Promises of rapid success in new drug process.
Assemblers	None yet.	Getting private investment involved at this stage.

Source: In Realis Investment Report

Projections of Individuals or Companies

Although the general information and insights provided by the organizations listed above project dramatic opportunities in the nanotech industry, specific projections, especially with regard to real business plans, provide a particularly down-to-earth view of the future of technology. A list of some relevant projections of this type is shown below.

- Nanotechnologies, Inc. (Austin, Texas) is currently selling nanomaterials and plans to materially increase production levels within the next year.
- Applied Nanotechnology (Austin, Texas) is currently producing nanotubes for use in portable X-ray devices and large illuminated displays. The company has recently signed an agreement with Mitsui of Japan to evaluate future uses of nanotechnology.
- C Sixty (Houston) currently has two products in advanced pre-clinical testing for the treatment of HIV.
- In 2002, Carbon Nanotechnologies, Inc. (Houston) announced an agreement with DuPont Central Research & Development (CR&D) to "license CNI's patented laser-oven buckytube production process for use in the area of field emission flat panel displays. DuPont CR&D, working with DuPont Displays, will use the buckytubes (single-wall carbon nanotubes) produced by this specialized process to allow a new generation of flat panel displays."[54]
- DuPont and Air Products have formed a 50/50 joint venture (DA Nanomaterials) to "develop, manufacture, and market colloidal silica based slurries for electronic precision polishing and chemical mechanical planarization (CMP)."[55]
- "DuPont Titanium Technologies, part of a wholly-owned subsidiary of DuPont, closed an intellectual property agreement with NanoSource Technologies, Inc., a nanomaterials company in Oklahoma City in 2002."[56]
- Hosokawa, a Japanese manufacturer and distributor of materials, has established the Hosokawa Nanoparticle Technology Center in Minneapolis, Minnesota. "The Center is a newly established operation dedicated to the development, manufacture, and commercialization of nanoparticles and composite materials."[57]
- In 2002, DeGussa announced that the company, through its Creavis Technologies & Innovations Division, has been working to develop industrial products based on the lotus effect (polymeric nanoparticles), which is a way of achieving a hydrophobic surface that is easy to clean and water-repellent. The spectrum of possible commercial developments ranges from roof tiles through exterior house paints, plastics products, wood varnishes, paint raw materials, glass and metal, textiles, and car polishes to paper and powder coatings with lotus effect.
- Samsung, through the Samsung Advanced Institute of Technology, has been working with flat-panel nanotube displays for some time and plans to introduce the first of these products within 2003 or 2004.

[54] Carbon Nanotechnologies Inc. Press Release. "CNI Licenses Production Process to DuPont." January 8, 2002
[55] DuPont Press Release. "DuPont I Technologies and Air Products Announce Joint Venture." January 9, 2001
[56] Fried, Jayne. "DuPont buys IP for Nanomaterial Seen as Hot in Cosmetics, Coatings." *Small Times Magazine* July 17, 2002
[57] Hosokawa NanoParticle Technology Center, Coatings." http://www.hosokawanano.com/web/nano/index.htm

- In 2002, Hewlett-Packard Labs announced "that they had created a new kind of extremely minute circuit for computer chips. These new circuits measure less than one square micron and can be used to create memory chips or to augment processors."[58] HP asserts that the product will be on the market in the next three years.
- In 2001, General Motors announced "the first-ever automotive production part built out of an olefinic nanocomposite made of a nano-clay compound. The part is a step assist for GM Safari and Astro vans."[59]
- Quantum Dot Corporation, a leader in quantum dot biotechnology applications, announced on November 14, 2002 the launch of its first Qdot product. QDC claims that the Qdot 605 Streptavidin Conjugate enables dramatic improvements in a wide range of bio-sensing applications.[60]
- BASF is "using nanotechnology to improve its existing range of products and to create new ones. BASF already realizes 10% of sales from nanotechnology and allocates 10% of its research resources to the sector. Existing BASF nanoproducts include UV-resistant sunscreens, transparent floor coatings, and pigments. Future products will include hydrogen adsorption nanocubes for fuel cells and transparent "lotus effect" films for windows that repel dirt and water."[61]
- IBM has recently announced that it plans to introduce new high-density data storage devices, called nanodrives, within the next three years. The project is called Millipede and was discussed extensively in the January 2003 edition of *Scientific American*.
- In 2002, Intel announced plans to spend $12.5 billion over two years on a variety of chip-making technologies. They believe one of those technologies could create transistors with 50 nanometer dimensions.
- "Samsung Corning expects to commence commercial production of nanopowders in 2003 and is targeting sales of $23 million (U.S.) in 2005."[62]

Forecasting Methodologies

Forecast Underpinnings

As indicated in the previous sections, the term nanotechnology embraces a wide range of technologies and market opportunities and, thus, a number of different projections are required for a meaningful technology forecast of the field. The forecasts presented above are based on three approaches to the forecasting effort:

- An examination of fundamental driving forces.
- Projections by organizations involved in various areas of nanotechnology.
- Projections by individuals or companies active in various areas of nanotechnology.

58 Spooner, John. "HP uses nanotechnology for new circuit." *CNET News.com* September 9, 2002
59 Leaversuch, Robert. "Nanocomposites broaden roles in Automotive, Barrier Packaging" *Plastics Technology* October 2001
60 Quantum Dot Inc. Press Release http://www.qdots.com/live/render/content.asp?id=15&press_id=27
61 Milmo, Sean. "BASF is poised to benefit from Nanotechnology." *Chemical Market Reporter* November 4, 2002
62 Advanced NanoTechnologies Press Release http://www.ant-powders.com/news.html

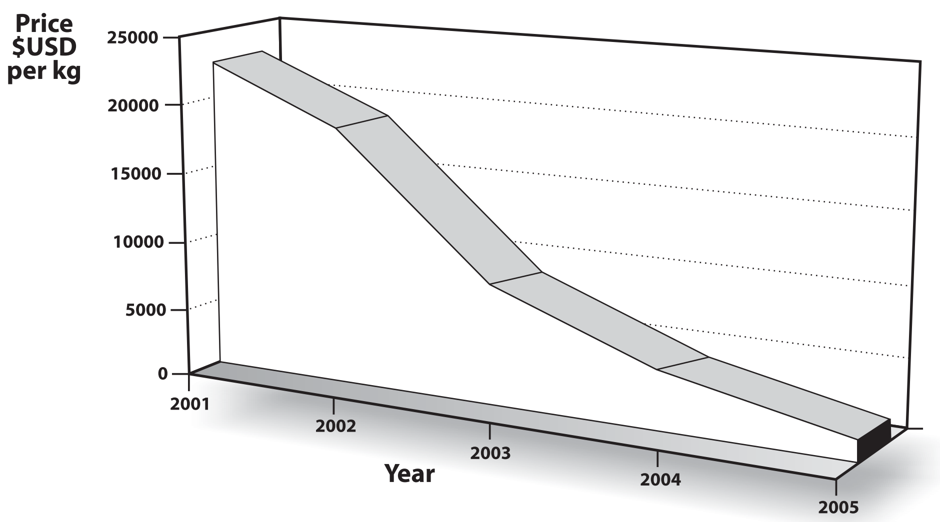
Extrapolation Techniques

To gather input data and insights to support each of these approaches, the authors placed primary emphasis on the use of literature searches and expert opinion techniques. Although we tried to identify trends in advances in technology in order to use extrapolation techniques, we were able to find little relevant time series data, and what we did find was often unreliable and confusing. For example, it is widely acknowledged that the price of producing material for nanotech research and development, e.g., fullerenes and nanotubes, is decreasing rapidly (see Exhibit 14). However, currently there is a wide range of prices for fullerenes for what would appear to be the same material. For example, an informal comparison of the cost of 99.5% pure C60 (fullerenes) from three different manufacturers revealed prices that ranged from as low as $33/gram to $795/gram. Overall, it appeared that extrapolation techniques would be of limited value for this forecast.

Literature Searches

In the conduct of this project, the authors placed considerable emphasis on searching various literature sources. Typically, each literature reference cites other references that lead to a constantly expanding database. Procedures were developed to identify and evaluate those sources that were the most current, authoritative, and relevant. Many of these sources offered projections on the rate of technical improvements and market development. Where appropriate, these projections were factored into the overall forecasts.

Exhibit 14
Fullerene Prices (2000–2005)



Source: Fullerene International Corporation, Japan.

Expert Opinion

To identify relevant experts, in addition to searching available literature sources, the authors attended a series of related meetings and conferences and contacted personal acquaintances in relevant fields. Particular effort was made to identify key players in the field and to establish personal relationships with them. It is anticipated that these personal relationships will be useful not only in gaining the most up-to-date information and insights, but also in identifying people who can contribute to periodic updating of the forecast. It is also envisioned that local advisory councils will be involved in examining the implications of nanotechnology applications in their areas.

To date, the authors have been able to build a network of experts by asking each of the people contacted to suggest other potential participants. Once appropriate experts were identified, it was necessary to engage them in the forecasting project. One technique that was used to engage experts was to write brief summaries of presentations by or conversations with various experts, and then, to send the summaries to the experts with requests for their review and comment. To date, this has been a very effective, though time-consuming, technique for gaining commitment to the forecasting project. Hopefully, in time these networks can be used to pass information among the different members of the group. Although it is beyond the scope of this project, it is envisioned that these networks can be kept intact to allow Texas State Technical College and TFI to periodically update the forecasts in the nanotechnology area.

It should be noted that, in conversations and messages with these experts, the authors always stressed the fact that this project is being sponsored by Texas State Technical College under the aegis of the Texas Higher Education Coordinating Board. This procedure added to the credibility of the forecast and enhanced cooperation.

Experts Consulted

People with whom the authors conducted personal, telephone, and/or e-mail conversations are listed below, together with a brief description of their input to the project. In actuality, each of these experts provided considerably more information and insights than those listed.

- **Conrad Masterson** (CEO, Nanotechnology Foundation of Texas) provided information on the overall state of nanotech in Texas.
- ***Dr. Denny Hamill*** (Vice President, Business Development, Nanotechnologies, Inc., and Board Member, Texas Nanotech Initiative) provided information on a broad range of subjects, including activities of the Texas Nanotechnology Initiative.
- ***Dr. Zvi Yaniv*** (President, Applied Technology, Inc.) provided information on the history of nanotech development and the current nanotech situation in Asia.
- ***Dr. Richard Fink*** (Vice President, Applied Technology, Inc.) provided information on the use of nanotechnology in illuminated displays.
- ***Dr. Dennis Wilson*** (Chief Technology Officer, Nanotechnologies, Inc.) provided information on the manufacture and use of nanomaterials.

- ***Dr. Michael D. Mehta*** (Associate Professor of Sociology, University of Saskatchewan) provided insights into the legal and sociological implications of nanotech industries.
- ***Dr. Edward T. Michalson*** (Technical Advisor, Winstead Sechrest & Minick) provided information on the floridation of nanotubes.
- ***Ellery R. Buchanan*** (Executive Vice President, New Jersey Nanotechnology Consortium) provided information on the nanotech activities in New Jersey.
- ***Dr. Douglas Natelson*** (Associate Professor, Department of Physics, Rice University) provided information on a nanotechnology course being conducted at Rice University.
- ***Dr. Vicky Colvin*** (Professor, Department of Chemistry, Rice University) provided information on a nanotech course being taught at Rice University.
- ***Dr. Stephen R. Wilson*** (Chief Scientific Officer, C Sixty, Inc.) provided information on the production and use of fullerenes.
- ***Eita Kitani*** (Manager, Nanotech Partners Limited [Mitsubishi Subsidiary]) provided information on the funding of nanotech in Japan.
- ***Kelly Kordzik*** *and* ***Ross Garsson*** (Nanotech Law Practice, Winstead Sechrest & Minick) provided information on the establishment of the firm's nanotech law practice.
- ***Dr. John N. Doggett*** (Director, Nano Manufacturing Technology Alliance, The University of Texas at Austin) provided information on the establishment of NMTA.
- ***Dr. Kevin D. Ausman*** (Executive Director, Center for Biological and Environmental Nanotechnology, Rice University) provided information on current research at CBEN and outlined some of the potential environmental challenges offered by nanotech.
- ***Bill Mays*** (Fab Manager, Electronics Technology, Texas State Technical College West Texas) provided information on the organization and activities of the Nanotechnology Curriculum Consortium.
- ***Paul F. McClure*** (Chairman and CEO, Xidex Corporation) provided information on atomic force microscopes.
- ***Dr. Donald A Tomalia*** (President and CTO, Dendritic Nanotechnologies) provided insights in the production and application of dedritic nanomaterials.
- ***Dr. Norman Schumaker*** (CEO and President, Molecular Imprints, Inc.) provided information on step-and-flash imprint technology.
- ***Charles E. Sweeny*** (President and CEO, NanoBioMagnetics) provided information on the biological placement of ferrite buckyballs by magnetic means.
- ***William E. Nasser*** (President and CEO, Southwest Nanotechnologies) provided information on his company's nanoparticle product methods.
- ***Matthew S. Blanton*** (CEO and Managing Partner, STARTech Early Ventures) provided information on current venture capital funding procedures.

- ***Henley Curtis Hoge, IV*** (RR Donnelley Financial) provided information on current venture capital funding procedures.
- ***David Sun*** (Vice President, Business Development & Marketing, Xeotron) provided information on current venture capital funding procedures.

Our contacts with these experts, together with literature searches, provided us with the insights outlined in the preceding paragraphs.

Nanotechnology: Potential Impacting Factors

The forecasts presented in the previous section are based on projections that the authors believed to be the most likely or, as such forecasts are often referred to, a "surprise free" scenario. However, in a technology as dynamic as nanotechnology, various unexpected breakthroughs, events, or decisions could materially change the nature, rate, and implications of technical advances and market developments. In order to identify and examine possible influencing factors, the authors scheduled and conducted a meeting of a group of individuals with proven qualifications in a number of different nanotech areas. This group included 10 people from universities, nanotech companies, a consulting company, a law firm, and a venture capital company (see Appendix E).

The meeting was held in the Campus Club of the University of Texas at Austin on February 15, 2003 and used a Nominal Group Conference format. First, meeting participants were asked to individually identify and write down any items that might affect the nature of nanotechnology development in Texas. These items were then recorded and distributed to participants (see Appendix F). The group next discussed each of the recorded items. Finally, each participant was asked to rate each of the items in terms of its possible impact on each of the four nanotech areas, the probability of the item occurring, and the time at which the item would most probably occur. Appendix G presents the rating instructions.

Later, the ratings were averaged and ranked in the order of overall importance with regard to each nanotech area. For the overall importance rating, impact and probability were rated twice as high as timing. The results of this process are presented in Appendix H. In this appendix, items that are judged to accelerate nanotech development in each area are shown in one list and items that are judged to deter development are shown on another list. On one item (Item 52), participants differed significantly on whether the element would accelerate or deter development, so that item is shown on all lists. (*Note***:** Item numbers in this section refer to the list presented in Appendix F).

The following comments are based on both the results of the ratings and the discussion that took place during the meeting. For the most part, there were close parallels between the discussions and the ratings. However, there were some items that invoked a great deal of conversation but were not rated as being particularly important, and there were other items in which the opposite was true.

Overall, the discussions centered on four groups of players, i.e., universities, large companies, entrepreneurial companies, and government entities, and the relationships among them. In general, participants agreed that each group had an important role to play in nanotech development in the state and that coordination was desirable. One participant noted that there are typically four **stages in the life cycle of a new technology**:

- *Discovery:* The genesis of the idea.
- *Founding:* The idea has enough clarification to allow for commercial development and intellectual property protection.
- *Maturing:* The idea has a demonstrated market and is generating significant revenue.
- *Reinvention:* The idea has reached its maturity and succeeding ideas begin to develop.

Participants agreed that universities and industrial R&D laboratories were the groups most important in the discovery stage, entrepreneurial companies in the founding stage, and large companies in the maturing stage. No one believed that nanotechnology is anywhere near the reinvention stage.

It is interesting to note that an event that would have a major impact on accelerating the development of a vibrant nanotech industry in Texas is the occurrence of a **major commercial success** (Items 7, 6, and 11). The extremely high ratings for such events indicate that the participants not only believed they were important, but also that there was a high probability of such events occurring in the relatively near future.

Another event that was envisioned as providing a major advance in nanotech development was the **entry of a large company**, such as IBM, AMD, or Motorola, into the nanotech field (Item 2). In general, it was felt that small entrepreneurial companies were important in demonstrating the value of new nanotechnologies, but that capitalizing on them would require the resources and commitment of larger organizations.

There was considerable discussion about the most appropriate **relationships between universities and entrepreneurs**. Although there was considerable agreement that cooperation between and among these groups was important (Items 39, 4, 42, 43, and 51), there were disagreements as to what shape that cooperation should take. For example, to the suggestion that universities should coordinate research activities, it was pointed out that universities normally prefer to establish special competency in an independent area rather than be part of a research association and that universities train and encourage students to do independent research rather than participate in group activities.

There was some interest in the **State of Texas focusing its efforts** in a particular area of nanotechnology, rather than spreading its efforts among many areas (Items 52, 5, and 8).

Specific areas that were suggested were nanobiotechnology, electronics, computers, and nanoenergy. However, there was some sentiment that, because of California's strength in electronics or computers, the state should not concentrate on those areas but rather on nanoenergy where it would have a strong position.

Participants rated **state government support** as an important element of success (Items 16, 27, 28, and 30). Although such support is viewed as important, there was considerable question about the probability of strong funding under the current budget situation. **Funding from venture capital firms** is also predicted to be limited in the near future. However, it was indicated that small firms would be more likely to receive such funding if they could demonstrate either current or clearly-defined future income (Items 8 and 37).

There were strong feelings that the **availability of a skilled workforce** would be an important element in nanotech development in the state, and, thus, a strong educational program was essential (Items 19 and 25).

One subject that evoked considerable discussion among participants was potential **health, safety, and environmental problems** associated with nanotechnology. There was a strong belief that a major incident in one of these areas would have a serious negative impact on nanotech development (Items 22 and 18). In fact, it was pointed out that even public perceptions of potential problems could result in overly restrictive regulations that would delay development (Item 13). It was also noted that very little research has been done to examine potential problems in these areas. Based on experiences in the biotechnology and nuclear energy areas, it was projected that arguments about the safety of nanotechnologies might not be based on scientific research at all, but rather on emotional reactions. However, it was pointed out that research-based data will be essential to bringing reality into discussions.

Participants also noted that **investor disappointment** and **public belief** that the technology was being "over-hyped" could deter nanotech development (Items 34 and 10). Participants indicated that continuation of current **economic problems** could be a major deterrent to development (Item 21). Other potential deterring factors identified were **too narrow of a focus** in development efforts (Items 32 and 52), possible loss of talent to other areas (Item 32), **failure to understand the technology development process** (Item 48), and a possible **terrorist attack** (Item 38). Strangely enough, given the current national security threat, the possibility of a nanotechnology being used to detect and defeat an enemy biological agent was rated last in importance in accelerating nanotech development (Item 23).

Summarizing the results of the meeting and ratings, it is apparent that nanotechnology is in a state of flux. Development is being restricted to some degree by current economic conditions and could seriously be delayed by unanswered questions about health, safety, or the environment. However, there are many important events and breakthroughs that could significantly advance the development of nanotechnology in Texas.

Final Comments

The reduction of many substances to the nanometer size results in very significant, fundamental changes in physical properties, such as color, magnetism, strength, and electric and heat conductivity. To the extent that these nanoparticles can be characterized, organized, and manipulated, they promise to make radical changes in our business, professional, and personal lives.

Although the true importance of nanotechnology has not yet been truly defined or appreciated, over the last few years basic nanoscience research has provided sufficient understanding of nano phenomina to allow the development of commercial products and services. The exact nature and size of potential nanotech markets are unclear at this time. However, there is little doubt that these new technologies promise almost unlimited business and associated employment opportunities. Moreover, these opportunities could expand very rapidly, if technical breakthroughs, now envisioned are, indeed, realized.

Although community and technical college deans and other instructional officers should not over-react to these possibilities, the colleges should be alert to the impact that advances in nanotechnology may have on current programs, such as those involving semiconductor manufacturing. The Nanotechnology Curriculum Consortium will provide these colleges with additional information on which to base future nanotech-related decisions. It is envisioned that the information and insights contained in this report will support the efforts of this Consortium.

Because of the potential importance of nanotechnology to the long-term economic prosperity of Texas, it is essential that the community and technical colleges of the state be positioned to react quickly to expansions in the nanotech industry to assure their students the special opportunities characteristic of early entry into a burgeoning market place.

List of Exhibits

A Appendix: Venture Capitalists at NanoVentures 2003

ARCH Venture Capital
- Clinton Bybee

Austin Ventures
- Kevin Lalande
- Mark Mellar Smith

CenterPoint Ventures
- Terrance Rock

Cogene Biotech Ventures
- Dr. Christopher W. Kersey

Genesis Park
- Rob Donnelly

Lux Capital
- Josh Wolfe

Patriot Venture Partners
- Mark C. Thaller

Sevin Rosen Funds
- Daniel Leff
- Charles Phipps
- Al Schuele

Vanguard Venture Partners
- Dr. Robert Ulrich

Vortex Partners
- Victor Liu
- Dr. Rob Miles

B Appendix: Employment Opportunities in Nanotechnology, Technicians with Associate Degrees

Job Descriptions

Title	**Medical Technologist**
Salary	**$22 to $25 per hour**
Nanotechnology Area	**Life Sciences**

Education/Training: Two-year associate degree program in medical technology and one year of direct work experience in field of hire. American Society of Clinical Pathologist (ASCP) certification may also be required.

Special Skills: These graduates will be required to provide advanced technical skills in performing and analyzing various clinical laboratory tests and procedures. These tests and procedures could include assays, microscopy, DNA sequencing, etc. that are built on new nanotechnology advances.

Job Description: This person will be responsible for performing various types of medical procedures and tests that take advantage of new advances in nanotechnology. For example, these technologists might be required to perform an assay that uses quantum dots as the tagging element. This person will have to be able to recognize that the color of each of the quantum dots represents a different structure (as explained in the Life Sciences section of the report). Additionally, these technologists might eventually use some of the new DNA tests (lab-on-a-chip) to perform sequencing. Some basic electron microscopy specimen preparation and analysis may also be required.

Title	**Electronics Technician**
Salary	**$20 to $22 per hour**
Nanotechnology Area	**Tools/Instrumentation, Materials, Life Sciences, and Electronics**

Education/Training: Two-year associate degree program in electronics.

Special Skills: Familiarity with electronic equipment and experimental devices common to an electronics repair facility (digital and analog circuitry, diagram and circuit reading).

Job Description: Perform specialized technical tasks in the design, construction, operation, and maintenance of complex electronic equipment and experimental instruments and apparatus to include the design and modification of circuits and the development of plans. These instruments include computers, oscilloscopes, voltmeters, sensors, actuators, analog-to-digital converters, and image capturing equipment. A foundation in these basic skills will be used in all of the nanotechnology areas to control, monitor, and record various process phenomena. These skills will continue to be necessary as companies progress from the R&D stage to manufacturing.

Title	**Licensed Electrician/Journeyman Electrician**
Salary	**$18 to $22 per hour**
Nanotechnology Area	**Tools/Instrumentation, Materials, Life Sciences, and Electronics**

Education/Training: Practical and theoretical work at two-year college in electrician program.

Special Skills: Ability to trace wiring and equipment diagrams. Familiarity with National Electric Code.

Job Description: This person will apply National Electric Code provisions that govern installation, modifications, and repair of electrical wiring and equipment in commercial and laboratory buildings (wiring panels, AC/DC low voltage). This person will also be responsible for the maintenance, repair, installation, and/or modification of electrical systems, motors, valves, sensors/ actuators, electrical control, and related electrical drive units as related to a nanotechnology laboratory/ manufacturing environment.

Title	**Draftsman/Mechanical Designer**
Salary	**$13 to $18 per hour**
Nanotechnology Area	**Materials and Electronics**

Education/Training: Two-year associate degree program in engineering design graphics.

Special Skills: Familiarity with standard drafting practices and computer-aided drafting software packages including Autocad, Pro/E, Inventor, and Mechanical Desktop.

Job Description: Ability to analyze complex design data and prepare clear, complete, and accurate plans, models, and detailed drawings from rough or detailed sketches or notes using standard software design packages. These skills will be necessary in the fabrication of prototypes and assemblies for nanotechnology companies in all stages of development (R&D to full-fledged production).

Title	**Machinist**
Salary	**$10 to $15 per hour**
Nanotechnology Area	**Materials**

Education/Training: Practical and theoretical work at two-year college in machinist program.

Special Skills: Experience with computer numerically controlled equipment. Ability to measure work carefully using precision tools such as micrometers.

Job Description: This person will be responsible for fabricating, maintaining, and repairing metal objects through the operation of lathes, shapers, planers, milling machines, drill presses, hydraulic presses, and similar equipment. This person will be performing milling and lathe work on a wide variety of equipment used in the nanomaterials manufacturing environment, including pumps, valves, flanges, and general production prototypes and assemblies.

Title	**Mechanical Technician**
Salary	**$8 to $12 per hour**
Nanotechnology Area	**Materials**

Education/Training: Moderate amount of practical based coursework at two-year college in some kind of machinist or automotive technology program.

Special Skills: This work will probably require someone with six months of experience in performing operational checks and repair on the functional parts of mechanical equipment and machinery or related experience.

Job Description: This person will conduct routine operational checks related to maintenance and repair of mechanical equipment and facilities. These duties include inspection, testing, cleaning, lubrication, and repair or replacement of defective parts. This person must also be able to perform simple milling machine, shaper, and metal fabrication work that requires welding.

Title	**Welder**
Salary	**$15 to $18 per hour**
Nanotechnology Area	**Materials, Life Sciences**

Education/Training: Two-year associate degree program in welding technology.

Special Skills: Basic blueprint diagram and sketch reading, plasma arc cutting, oxy-fuel welding and cutting.

Job Description: This person will be responsible for various types of weld preparation, welding, and weld finishing operations. These operations will be used in the fabrication of laboratory and production equipment to mechanical drawings, specifications, or other forms of instruction. As such, this person will be responsible for assisting scientists and engineers in the fabrication of systems used in the manufacture of nanomaterials for biological and non-biological systems. These systems include piping for gas delivery and recovery, nanomaterials production equipment, and vacuum systems.

C Appendix: Comparative Nanotechnology Expenditures

Comparative Nanotechnology Spending[1]

	Texas	CA	NY	MA	UK	Ger	Korea	Japan
Gross State/ Domestic Product	$768B	$1.36T	$755B	$239B	$1.36T	$1.94T	$765B	$3.15T
State Budget	$58B	$98.9B	$89.6B	$12.5B	NA	NA	NA	NA
Population	21.3M	34.5M	19.0M	6.3M	59.6M	83.0M	47.9M	127M
Workforce	10.3M	17.1M	8.9M	3.2M	29.2M	40.5M	22.0M	68.0M
Gov't Nano Funding	$0.5M	$100M	$100M	NA	~$50m	NA	$160m	$650m
Geographic Area (square kilometers)	681,000	425,600	128,900	21,500	244,800	357.000	98,500	377,800
Nano Funding per Capita	**$0.02**	**$2.90**	**$5.26**	**NA**	**$0.84**	**NA**	**$3.34**	**$5.16**
Patents per 10,000 Employees/Rank	7.3/18	13.0/1	8.9/12	11.7/5	NA	NA	NA	NA
Venture Capital Investment Rank	15	1	7	2	NA	NA	NA	NA

NA= Not available or not applicable

[1] Data are generally for 1999 except for Nano Funding, which are 2001 data for states and 2002 data for foreign governments.

D Appendix: Nanotechnology Classification Schemes

Rice University Center for Nanoscale Science and Technology

1 Wet

2 Dry

3 Computer Simulation

Applied Nanotech, Inc.'s Seven Pillars of Nanotechnology

1 Ultra-thin layers

2 Top-down nanostructures

3 Bottom-up structures

4 Ultra-precise surface preparation

5 Analytical instruments for nanostructures

6 Integration of nanomaterials and molecular structures

7 Nanotechnology and biotechnology convergence

The University of Texas at Austin, Professor P. J. Ferriera's Course Classification Schemes

Characterizations

1 Thermal characterization

2 Electrical characterization

3 Magnetic characterization

4 Porosity characterization

5 Optical characterization

6 Mechanical characterization

Properties

7 Physical-chemical properties

8 Mechanical properties

9 Electrical properties

10 Magnetic properties

11 Thermal properties

12 Optical properties

Applications

13 Nanomedicine

14 Nanoelectronics

15 Nano-devices

16 Nanorobotics

17 Quantum dots

18 Magnetic recording

19 DNA probing

20 Drug delivery

21 BioMems

22 Things that think

23 Wired humans

Scientific American, 10 Chapters in September 2001 Edition

24 Overview – Little Big Science

25 Nanofabrication – The Art of Building Small

26 Nanophysics – Plenty of Room Indeed

27 Nanoelectronics – The Incredible Shrinking Circuit

28 Nanomedicine – Less is More in Medicine

29 Nanovisions – Machine Phase Technology

30 Nanofallacies – Of Chemistry, Love and Nanobots

31 Nanoinspirations – The Once and Future Nanomachine

32 Nanorobotics – Nanobot Construction Crews

33 Nanofiction – Shamans of Small

National Science Foundation, Nanoscale Science and Engineering Centers

34 Columbia University Center for Electron Transport in Molecular Nanostructures

35 Cornell University: Center for Nanoscale Systems in Information Technologies. The Center, based at Cornell University, also includes participants at Colgate University, University of New Mexico, Brigham Young University, and Pomona College and strong collaborations with industrial partners, including Corning, IBM, Motorola, and NonVolatile Electronics.

36 Harvard University: Science of Nanoscale Systems & Their Device Applications. This center is a collaboration between Harvard University, Massachusetts Institute of Technology, University of California at Santa Barbara, and Museum of Science in Boston, with participation by Delft University of Technology (Netherlands), the University of Tokyo (Japan), Brookhaven National Laboratory, Oak Ridge National Laboratory, and Sandia National Laboratory.

37 Northwestern University: NSEC for Integrated Nanopatterning and Detection (Chemical and Biological Sensing) Technologies

38 Rensselaer Polytechnic Institute Center for Directed Assembly of Nanostructures

39 Rice University: Center for Biological and Environmental Nanotechnology (CBEN)

Nanotechnology Foundation of Texas, Commercial Application Classification

40 Basic research

41 Tools, test equipment, manufacturing equipment

42 Specialty chemical applications

43 Medical applications

44 Composite and smart materials

45 Molecular electronics

46 Other applications

Appendix E

Appendix: Nominal Group Conference Participants

Kevin Ausman, Ph.D.	Executive Director *Center for Biological & Environmental Nanotechnology* Rice University 08 Herman Brown Hall, MS 63 Houston, TX 77252	(713) 348-8212 ausman@rice.edu www.rice.edu
Richard Fink, Ph.D.	Vice President *Applied Nanotech, Inc.* 3006 Longhorn Boulevard, Suite 107 Austin, TX 78758	(512) 339-5020 x 130 Fax (512) 339-5021 dfink@appliednanotech.net www.sidiamond.com
Denny Hamill, Ph.D.	Vice President, Business Development *Nanotechnologies* 1908 Kramer Lane, Building B, Suite L Austin, TX 78758	(512) 491-9500 x 213 Fax (512) 491-0002 denny.hamill@nanoscale.com www.nanoscale.com
Kelly K. Kordzik, Esq.	*Winstead Sechrest & Minick* 100 Congress Avenue Suite 100 Austin, TX 78701	(512) 370-2851 Fax: (512) 370-2850 kkordzik@winstead.com www.winstead.com
Christopher Shonk	Partner *Gendeavor Consulting Group* 10301 FM 2222, Suite 1026 Austin, TX 78730	(512) 431-3371 Fax (512) 431-3371 cshonk@gendeavor-cg.com www.gendeavor-cg.com
David Smith	Vice President *Technology Futures, Inc.* 13740 Research Boulevard, Building C Austin, TX 78750	(512) 258-8898 Fax (512) 258-0087 dsmith@tfi.com www.tfi.com
Robert Wenz, Ph.D.	Associate Director *Center for Nano- & Molecular Science & Technology* *University of Texas at Austin* WEL 3.202, 1 University Station, MC A5300 Austin, TX 78712-0165	(512) 471-3655 Fax: (512) 471-3389 bwenz@mail.utexas.edu www.utexas.edu
Dennis Wilson, Ph.D.	Chief Technology Officer *Nanotechnologies* 1908 Kramer Lane, Building B, Suite L Austin, TX 78758	(512) 491-9500 x 208 Fax (512) 491-0002 dennis.wilson@nanoscale.com www.nanoscale.com
Zvi Yaniv, Ph.D.	President & CEO *Applied Nanotech, Inc.* 3006 Longhorn Boulevard, Suite 107 Austin, TX 78758	(512) 339-5020 x 103 Fax (512) 339-5021 zyaniv@appliednanotech.net www.sidiamond.com

Observers/Staff

Michael A. Bettersworth	Associate Vice Chancellor *Texas State Technical College* System Operations Office 3801 Campus Drive Waco, TX 76705	(254) 867-3991 Fax (254) 867-3993 bettersworth@systems.tstc.edu www.tstc.edu
Henry Elliott	Research Associate *Technology Futures, Inc.* 13740 Research Boulevard, Building C Austin, TX 78750	(512) 258-8898 Fax (512) 258-0087 helliott@tfi.com www.tfi.com
Debra Robison	Administrative Director/Recorder *Technology Futures, Inc.* 13740 Research Boulevard, Building C Austin, TX 78750	(512) 258-8898 Fax (512) 258-0087 drobison@tfi.com www.tfi.com
John H. Vanston, Ph.D.	Chairman/Facilitator *Technology Futures, Inc.* 13740 Research Boulevard, Building C Austin, TX 78750	(512) 258-8898 Fax (512) 258-0087 jvanston@tfi.com www.tfi.com

F Appendix: List of Nominal Group Items

1 A non-nanotech energy source is developed.

2 Large companies commit to nanotech R&D in Texas, creating jobs and drawing good people from the rest of the country.

3 Restrictive intellectual property policies are developed that inhibit scientific development and collaboration between various nanotech groups in the state.

4 Free-flowing communication and collaboration between all Texas universities in nanospace, linked to large corporations on an international level.

5 A practical breakthrough occurs in the use of nanotechnology related to computer architecture.

6 A product using nanotech is commercialized that results in significant revenue (i.e., more than a billion dollars per year).

7 The first widely successful use of "true" nanotechnology.

8 Venture capitalists begin to have positive perception of nanotechnology as a reality, rather than just hype.

9 A clear definition of the roles of universities and entrepreneurs is established.

10 The amount of hype relative to success continues to grow.

11 There are one or two major commercial breakthroughs.

12 Money becomes available to hire more nanotech graduate students, enticing more students to go into the nanotech field.

13 The nanotech field is excessively regulated because of the fear of potential health and safety problems.

14 Texas chooses not to focus on a limited set of nanotechnologies.

15 There is greater state nanotech industry focus.

16 State government and energy companies support a specific nanoenergy initiative.

17 There are scientific breakthroughs that result in ownership of intellectual property.

18 The first example of a nanotech-related health or environmental problem arises.

19 A readily-available skilled workforce is developed.

20 The nanotech community creates an "umbrella" that defines nanotechnology and applies it to the state of Texas.

21 The current economic slowdown continues, and venture capital dries up.

22 A consensus develops that nanotechnology is bad for the environment.

23 There are some early successes in the use of nanotechnology in the detection and defeat of a bioagent.

24 Strong leadership is shown in government, legislative, academic, financial, and community sectors.

25 There are significant increases in the education in and awareness about nanotechnology in the corporate, legislative, consumer, and investment communities, starting at the high-school level.

26 Significant cooperation is established between a Texas company and a foreign company in the nanotech area.

27 The state provides research funding at a level comparable to that in California or New York. This funding will draw the intellectual property and skilled workforce needed for success in the nanotech field.

28 The state develops a rational strategic plan/roadmap on nanotech, including a concise marketing and imaging plan.

29 The "incubator" approach to nanotech development is abandoned in favor of an "IP accelerator" approach.

30 Texas undertakes a bold initiative similar to those undertaken by California and the northeast states.

31 The state continues to focus funding on old technologies.

32 Separate, narrow nanotech initiatives without a common identity and needs continue to proliferate.

33 Economic factors push nanotech manufacturing offshore.

34 There is investor disappointment in nanotechnology.

35 A nanotech design center is created in Texas by a large company.

36 Because of the aging population, increased funding is provided for geriatrics research. Moreover, the insatiable demand for information storage and increased bandwidth promote nanotechnology development.

37 More dollars are made available for nanotech development. A joint venture is established that is a unification of nanotech dollars and entrepreneurs. Funding is focused on small companies that produce instant revenue.

38 Terrorism becomes an increasing problem.

39 Texas universities and small nanotech companies take the lead in developing standard tools for fabrication and characterization of nanotech materials and devices.

40 Other regions of the country draw nanotech talent from the state.

41 Texas attempts to compete in areas in which other states have already established a monopoly.

42 State schools, such as the University of Texas at Austin, become more effective at the commercialization of intellectual property they develop.

43 The state focuses on the convergence of nanotech, biotech, computers, microprocessors, memory, etc.

44 The state government provides assistance and intervention in channeling federal nanotech dollars into Texas universities and small companies.

45 There continues to be a lack of "churn" and collaboration in the state's nanotech industry.

46 New forms of computational resources, such as quantum, biological, and analog, are not adopted by the state.

47 There continues to be a lack of specialized nanotech infrastructure and people in the state.

48 Texas is not able to meet all of the areas of the innovation life-cycle (i.e., discovery, founding, maturing, and reinvention).

49 Steps are taken to assist the easy movement of nanotech intellectual property from the state's universities to industry without upfront payment.

50 More nanotech corridors are formed (e.g., Austin-San Antonio).

51 There is an effort to contact the nanotech companies that already exist in Texas to see what they have to offer and to use their expertise and tools.

52 Nanotech groups in Austin focus on nanoelectronics.

53 Texas leaders fail to realize that nanotechnology is a global industry.

Appendix G: Nominal Group Rating Instructions

Rating Instructions

Effect

S The event will accelerate the development of a Texas nanotech industry in this nanotech area

L The event will deter the development of a Texas nanotech industry in this nanotech area

Importance

9 Will very significantly affect the development of a Texas industry in this nanotech area

3 Will moderately affect the development of a Texas industry in this nanotech area

1 Will have little or no effect on the development of a Texas industry in this nanotech area

Probability of Occurrence

9 Will almost certainly occur

3 Is as likely to occur as not to occur

1 Almost certainly will not occur

Time of Occurrence: If it does occur, it will occur . . .

9 Within the next two years

3 Within the next two to five years

1 In not less than five years

Rating Sheet

Importance

Item No.	Effect (S or L)	All	Inst., Tools, Comp.	Materials	Electronics/ Optics	Life Sciences	Probability	Time

H Appendix: Nominal Group Results

Life Sciences – Accelerate

#	Overall Average	Average Effect	Factor
7	8.4	A	The first widely successful use of "true" nanotechnology.
6	8.2	A	A product using nanotech is commercialized that results in significant revenue (i.e., more than a billion dollars per year).
11	7.6	A	There are one or two major commercial breakthroughs.
2	7.5	A	Large companies commit to nanotech R&D in Texas, creating jobs and drawing good people from the rest of the country.
4	6.6	A	Free flowing communication and collaboration between all Texas universities in nanospace, linked to large corporations on an international level.
42	6.3	A	State schools, such as the University of Texas at Austin, become more effective at the commercialization of intellectual property they develop.
24	6.3	A	Strong leadership is shown in government, legislative, academic, financial, and community sectors.
8	6.1	A	Venture capitalists begin to have positive perception of nanotechnology as a reality, rather than just hype.
27	6.0	A	The state provides research funding at a level comparable to that in California or New York. This funding will draw the intellectual property and skilled workforce needed for success in the nanotech field.
28	5.7	A	The state develops a rational strategic plan/roadmap on nanotech, including a concise marketing and imaging plan.
30	5.7	A	Texas undertakes a bold initiative similar to those undertaken by California and the northeast states.
39	5.5	A	Texas universities and small nanotech companies take the lead in developing standard tools for fabrication and characterization of nanotech materials and devices.
37	5.3	A	More dollars are made available for nanotech development. A joint venture is established that is a unification of nanotech dollars and entrepreneurs. Funding is focused on small companies that produce instant revenue.
17	5.2	A	There are scientific breakthroughs that result in ownership of intellectual property.
25	5.1	A	There are significant increases in the education in and awareness about nanotechnology in the corporate, legislative, consumer, and investment communities, starting at the high-school level.

52	5.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
51	5.0	A	There is an effort to contact the nanotech companies that already exist in Texas to see what they have to offer and to use their expertise and tools.
49	4.8	A	Steps are taken to assist the easy movement of nanotech intellectual property from the state's universities to industry without upfront payment.
19	4.8	A	A readily available skilled workforce is developed.
44	4.5	A	State government provides assistance and intervention in channeling federal nanotech dollars into Texas universities and small companies.
43	4.4	A	The state focuses on the convergence of nanotech, biotech, computers, microprocessors, memory, etc.
23	3.9	A	There are some early successes in the use of nanotechnology in the detection and defeat of a bioagent.
16	3.8	A	State government and energy companies support a specific nanoenergy initiative.
9	3.8	A	A clear definition of the roles of universities and entrepreneurs is established.
15	3.8	A	There is greater state nanotech industry focus.
20	3.7	A	The nanotech community creates an "umbrella" that defines nanotechnology and applies it to the State of Texas.
50	3.7	A	More nanotech corridors are formed (e.g., Austin-San Antonio).
35	3.7	A	A nanotech design center is created in Texas by a large company.
12	3.3	A	Money becomes available to hire more nanotech graduate students, enticing more students to go into the nanotech field.
29	3.2	A	The "incubator" approach to nanotech development is abandoned in favor of an "IP accelerator" approach.
26	2.6	A	Significant cooperation is established between a Texas company and a foreign company in the nanotech area.
5	2.3	A	A practical breakthrough occurs in the use of nanotechnology related to computer architecture.
46	2.3	A	New forms of computational resources, such as quantum, biological, and analog, are not adopted by the state.
36	2.0	A	Because of the aging population, increased funding is provided for geriatrics research. Moreover, the insatiable demand for information storage and increased bandwidth promote nanotechnology development.

Life Sciences – Deter

#	Overall Average	Average Effect	Factor
18	7.9	D	The first example of a nanotech-related health or environmental problem arises.
13	7.7	D	The nanotech field is excessively regulated because of the fear of potential health and safety problems.
34	7.2	D	There is investor disappointment in nanotechnology.
22	6.9	D	A consensus develops that nanotechnology is bad for the environment.
21	6.9	D	The current economic slowdown continues and venture capital dries up.
3	6.2	D	Restrictive intellectual property policies are developed that inhibit scientific development and collaboration between various nanotech groups in the state.
10	6.1	D	The amount of hype relative to success continues to grow.
48	5.7	D	Texas is not able to meet all of the areas of the innovation life-cycle (i.e., discovery, founding, maturing, and reinvention).
32	5.7	D	Separate, narrow nanotech initiatives without a common identity and needs continue to proliferate.
14	5.5	D	Texas chooses not to focus on a limited set of nanotechnologies.
47	5.5	D	There continues to be a lack of specialized nanotech infrastructure and people in the state.
38	5.1	D	Terrorism becomes an increasing problem.
52	5.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
40	5.0	D	Other regions of the country draw nanotech talent from the state.
41	4.7	D	Texas attempts to compete in areas in which other states have already established a monopoly.
1	4.7	D	A non-nanotech energy source is developed.
31	4.2	D	The state continues to focus funding on old technologies.
45	3.5	D	There continues to be a lack of "churn" and collaboration in the State's nanotech industry.
33	3.3	D	Economic factors push nanotech manufacturing offshore.
53	3.3	D	Texas leaders fail to realize that nanotechnology is a global industry.

Materials – Accelerate

#	Overall Average	Average Effect	Factor
7	8.4	A	The first widely successful use of "true" nanotechnology.
6	8.2	A	A product using nanotech is commercialized that results in significant revenue (i.e., more than a billion dollars per year).
11	7.6	A	There are one or two major commercial breakthroughs.
2	7.5	A	Large companies commit to nanotech R&D in Texas, creating jobs and drawing good people from the rest of the country.
39	7.2	A	Texas universities and small nanotech companies take the lead in developing standard tools for fabrication and characterization of nanotech materials and devices.
52	7.1	A/D	Nanotech groups in Austin focus on nanoelectronics.
4	6.6	A	Free flowing communication and collaboration between all Texas universities in nanospace, linked to large corporations on an international level.
42	6.3	A	State schools, such as the University of Texas at Austin, become more effective at the commercialization of intellectual property they develop.
24	6.3	A	Strong leadership is shown in government, legislative, academic, financial, and community sectors.
8	6.1	A	Venture capitalists begin to have positive perception of nanotechnology as a reality, rather than just hype.
27	6.0	A	The state provides research funding at a level comparable to that in California or New York. This funding will draw the intellectual property and skilled workforce needed for success in the nanotech field.
16	5.9	A	State government and energy companies support a specific nanoenergy initiative.
28	5.7	A	The state develops a rational strategic plan/roadmap on nanotech, including a concise marketing and imaging plan.
30	5.7	A	Texas undertakes a bold initiative similar to those undertaken by California and the northeast states.
43	5.4	A	The state focuses on the convergence of nanotech, biotech, computers, microprocessors, memory, etc.
37	5.3	A	More dollars are made available for nanotech development. A joint venture is established that is a unification of nanotech dollars and entrepreneurs. Funding is focused on small companies that produce instant revenue.

17	5.2	A	There are scientific breakthroughs that result in ownership of intellectual property.
19	5.1	A	A readily available skilled workforce is developed.
25	5.1	A	There are significant increases in the education in and awareness about nanotechnology in the corporate, legislative, consumer, and investment communities, starting at the high-school level.
51	5.0	A	There is an effort to contact the nanotech companies that already exist in Texas to see what they have to offer and to use their expertise and tools.
49	4.8	A	Steps are taken to assist the easy movement of nanotech intellectual property from the state's universities to industry without upfront payment.
44	4.5	A	State government provides assistance and intervention in channeling federal nanotech dollars into Texas universities and small companies.
35	4.5	A	A nanotech design center is created in Texas by a large company.
23	4.0	A	There are some early successes in the use of nanotechnology in the detection and defeat of a bioagent.
5	3.9	A	A practical breakthrough occurs in the use of nanotechnology related to computer architecture.
9	3.8	A	A clear definition of the roles of universities and entrepreneurs is established.
15	3.8	A	There is greater state nanotech industry focus.
20	3.7	A	The nanotech community creates an "umbrella" that defines nanotechnology and applies it to the state of Texas.
50	3.7	A	More nanotech corridors are formed (e.g., Austin-San Antonio).
26	3.4	A	Significant cooperation is established between a Texas company and a foreign company in the nanotech area.
12	3.3	A	Money becomes available to hire more nanotech graduate students enhancing more students to go into the nanotech field.
29	3.2	A	The "incubator" approach to nanotech development is abandoned in favor of an "IP accelerator" approach.
36	2.4	A	Because of the aging population, increased funding is provided for geriatrics research. Moreover, the insatiable demand for information storage and increased bandwidth promote nanotechnology development.
46	2.3	A	New forms of computational resources, such as quantum, biological, and analog, are not adopted by the state.

Materials – Deter

#	Overall Average	Average Effect	Factor
18	7.9	D	The first example of a nanotech-related health or environmental problem arises.
13	7.3	D	The nanotech field is excessively regulated because of the fear of potential health and safety problems.
34	7.2	D	There is investor disappointment in nanotechnology.
52	7.1	A/D	Nanotech groups in Austin focus on nanoelectronics.
22	6.9	D	A consensus develops that nanotechnology is bad for the environment.
21	6.9	D	The current economic slowdown continues and venture capital dries up.
3	6.2	D	Restrictive intellectual property policies are developed that inhibit scientific development and collaboration between various nanotech groups in the state.
1	6.2	D	A non-nanotech energy source is developed.
10	6.1	D	The amount of hype relative to success continues to grow.
48	5.7	D	Texas is not able to meet all of the areas of the innovation life-cycle (i.e., discovery, founding, maturing, and reinvention).
47	5.5	D	There continues to be a lack of specialized nanotech infrastructure and people in the state.
32	5.4	D	Separate, narrow nanotech initiatives without a common identity and needs, continue to proliferate.
38	5.1	D	Terrorism becomes an increasing problem.
40	5.0	D	Other regions of the country draw nanotech talent from the state.
14	4.8	D	Texas chooses not to focus on a limited set of nanotechnologies.
41	4.7	D	Texas attempts to compete in areas in which other states have already established a monopoly.
33	4.3	D	Economic factors push nanotech manufacturing offshore.
31	4.2	D	The state continues to focus funding on old technologies.
53	3.6	D	Texas leaders fail to realize that nanotechnology is a global industry.
45	3.5	D	There continues to be a lack of "churn" and collaboration in the state's nanotech industry.

Instruments, Tools, and Computers – Accelerate

#	Overall Average	Average Effect	Factor
7	8.4	A	The first widely successful use of "true" nanotechnology.
39	8.2	A	Texas universities and small nanotech companies take the lead in developing standard tools for fabrication and characterization of nanotech materials and devices.
52	8.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
6	7.8	A	A product using nanotech is commercialized that results in significant revenue (i.e., more than a billion dollars per year).
11	7.6	A	There are one or two major commercial breakthroughs.
2	7.5	A	Large companies commit to nanotech R&D in Texas, creating jobs and drawing good people from the rest of the country.
4	6.6	A	Free flowing communication and collaboration between all Texas universities in nanospace, linked to large corporations on an international level.
16	6.5	A	State government and energy companies support a specific nanoenergy initiative.
42	6.3	A	State schools, such as the University of Texas at Austin, become more effective at the commercialization of intellectual property they develop.
24	6.3	A	Strong leadership is shown in government, legislative, academic, financial, and community sectors.
8	6.1	A	Venture capitalists begin to have positive perception of nanotechnology as a reality, rather than just hype.
27	6.0	A	The state provides research funding at a level comparable to that in California or New York. This funding will draw the intellectual property and skilled workforce needed for success in the nanotech field.
43	6.0	A	The state focuses on the convergence of nanotech, biotech, computers, microprocessors, memory, etc.
51	5.9	A	There is an effort to contact the nanotech companies that already exist in Texas to see what they have to offer and to use their expertise and tools.
28	5.7	A	The state develops a rational strategic plan/roadmap on nanotech, including a concise marketing and imaging plan.
30	5.7	A	Texas undertakes a bold initiative similar to those undertaken by California and the northeast states.

19	5.5	A	A readily available skilled workforce is developed.
37	5.3	A	More dollars are made available for nanotech development. A joint venture is established that is a unification of nanotech dollars and entrepreneurs. Funding is focused on small companies that produce instant revenue.
17	5.2	A	There are scientific breakthroughs that result in ownership of intellectual property.
5	5.2	A	A practical breakthrough occurs in the use of nanotechnology related to computer architecture.
25	5.1	A	There are significant increases in the education in and awareness about nanotechnology in the corporate, legislative, consumer, and investment communities, starting at the high-school level.
49	4.8	A	Steps are taken to assist the easy movement of nanotech intellectual property from the state's universities to industry without upfront payment.
44	4.5	A	State government provides assistance and intervention in channeling federal nanotech dollars into Texas universities and small companies.
35	4.5	A	A nanotech design center is created in Texas by a large company.
9	3.8	A	A clear definition of the roles of universities and entrepreneurs is established.
15	3.8	A	There is greater state nanotech industry focus.
20	3.7	A	The nanotech community creates an "umbrella" that defines nanotechnology and applies it to the state of Texas.
50	3.7	A	More nanotech corridors are formed (e.g., Austin-San Antonio).
26	3.4	A	Significant cooperation is established between a Texas company and a foreign company in the nanotech area.
12	3.3	A	Money becomes available to hire more nanotech graduate students, enticing more students to go into the nanotech field.
23	3.2	A	There are some early successes in the use of nanotechnology in the detection and defeat of a bioagent.
29	2.4	A	The "incubator" approach to nanotech development is abandoned in favor of an "IP accelerator" approach.
46	2.3	A	New forms of computational resources, such as quantum, biological, and analog, are not adopted by the state.
36	2.2	A	Because of the aging population, increased funding is provided for geriatrics research. Moreover, the insatiable demand for information storage and increased bandwidth promote nanotechnology development.

Instruments, Tools, and Computers – Deter

#	Overall Average	Average Effect	Factor
52	8.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
34	7.2	D	There is investor disappointment in nanotechnology.
21	7.0	D	The current economic slowdown continues and venture capital dries up.
1	7.0	D	A non-nanotech energy source is developed.
13	6.9	D	The nanotech field is excessively regulated because of the fear of potential health and safety problems.
18	6.4	D	The first example of a nanotech-related health or environmental problem arises.
3	6.2	D	Restrictive intellectual property policies are developed that inhibit scientific development and collaboration between various nanotech groups in the state.
22	6.0	D	A consensus develops that nanotechnology is bad for the environment.
48	5.7	D	Texas is not able to meet all of the areas of the innovation life-cycle (i.e., discovery, founding, maturing, and reinvention).
14	5.5	D	Texas chooses not to focus on a limited set of nanotechnologies.
47	5.5	D	There continues to be a lack of specialized nanotech infrastructure and people in the state.
10	5.3	D	The amount of hype relative to success continues to grow.
40	5.0	D	Other regions of the country draw nanotech talent from the state.
41	4.7	D	Texas attempts to compete in areas in which other states have already established a monopoly.
32	4.6	D	Separate, narrow nanotech initiatives without a common identity and needs continue to proliferate.
33	4.0	D	Economic factors push nanotech manufacturing offshore.
31	3.9	D	The state continues to focus funding on old technologies.
38	3.8	D	Terrorism becomes an increasing problem.
53	3.6	D	Texas leaders fail to realize that nanotechnology is a global industry.
45	3.5	D	There continues to be a lack of "churn" and collaboration in the state's nanotech industry.

Electronics/Optics – Accelerate

#	Overall Average	Average Effect	Factor
7	8.4	A	The first widely successful use of "true" nanotechnology.
6	8.2	A	A product using nanotech is commercialized that results in significant revenue (i.e., more than a billion dollars per year).
52	8.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
11	7.6	A	There are one or two major commercial breakthroughs.
2	7.5	A	Large companies commit to nanotech R&D in Texas, creating jobs and drawing good people from the rest of the country.
5	7.4	A	A practical breakthrough occurs in the use of nanotechnology related to computer architecture.
4	6.6	A	Free flowing communication and collaboration between all Texas universities in nanospace, linked to large corporations on an international level.
42	6.3	A	State schools, such as the University of Texas at Austin, become more effective at the commercialization of intellectual property they develop.
24	6.3	A	Strong leadership is shown in government, legislative, academic, financial, and community sectors.
8	6.1	A	Venture capitalists begin to have positive perception of nanotechnology as a reality, rather than just hype.
27	6.0	A	The state provides research funding at a level comparable to that in California or New York. This funding will draw the intellectual property and skilled workforce needed for success in the nanotech field.
43	5.9	A	The state focuses on the convergence of nanotech, biotech, computers, microprocessors, memory, etc.
28	5.7	A	The state develops a rational strategic plan/roadmap on nanotech, including a concise marketing and imaging plan.
30	5.7	A	Texas undertakes a bold initiative similar to those undertaken by California and the northeast states.
39	5.5	A	Texas universities and small nanotech companies take the lead in developing standard tools for fabrication and characterization of nanotech materials and devices.
37	5.3	A	More dollars are made available for nanotech development. A joint venture is established that is a unification of nanotech dollars and entrepreneurs. Funding is focused on small companies that produce instant revenue.

17	5.2	A	There are scientific breakthroughs that result in ownership of intellectual property.
19	5.1	A	A readily available skilled workforce is developed.
25	5.1	A	There are significant increases in the education in and awareness about nanotechnology in the corporate, legislative, consumer, and investment communities, starting at the high-school level.
51	5.0	A	There is an effort to contact the nanotech companies that already exist in Texas to see what they have to offer and to use their expertise and tools.
49	4.8	A	Steps are taken to assist the easy movement of nanotech intellectual property from the state's universities to industry without upfront payment.
44	4.5	A	State government provides assistance and intervention in channeling federal nanotech dollars into Texas universities and small companies.
35	4.5	A	A nanotech design center is created in Texas by a large company.
16	4.1	A	State government and energy companies support a specific nanoenergy initiative.
9	3.8	A	A clear definition of the roles of universities and entrepreneurs is established.
15	3.8	A	There is greater state nanotech industry focus.
20	3.7	A	The nanotech community creates an "umbrella" that defines nanotechnology and applies it to the state of Texas.
50	3.7	A	More nanotech corridors are formed (e.g., Austin-San Antonio).
26	3.4	A	Significant cooperation is established between a Texas company and a foreign company in the nanotech area.
12	3.3	A	Money becomes available to hire more nanotech graduate students, enticing more students to go into the nanotech field.
29	3.2	A	The "incubator" approach to nanotech development is abandoned in favor of an "IP accelerator" approach.
46	2.5	A	New forms of computational resources, such as quantum, biological, and analog, are not adopted by the state.
36	2.2	A	Because of the aging population, increased funding is provided for geriatrics research. Moreover, the insatiable demand for information storage and increased bandwidth promote nanotechnology development.
23	2.1	A	There are some early successes in the use of nanotechnology in the detection and defeat of a bioagent.

Electronics/Optics – Deter

#	Overall Average	Average Effect	Factor
52	8.0	A/D	Nanotech groups in Austin focus on nanoelectronics.
34	7.2	D	There is investor disappointment in nanotechnology.
13	7.0	D	The nanotech field is excessively regulated because of the fear of potential health and safety problems.
21	7.0	D	The current economic slowdown continues and venture capital dries up.
18	6.4	D	The first example of a nanotech-related health or environmental problem arises.
3	6.2	D	Restrictive intellectual property policies are developed that inhibit scientific development and collaboration between various nanotech groups in the state.
22	6.0	D	A consensus develops that nanotechnology is bad for the environment.
48	5.7	D	Texas is not able to meet all of the areas of the innovation life-cycle (i.e., discovery, founding, maturing, and reinvention).
32	5.7	D	Separate, narrow nanotech initiatives without a common identity and needs continue to proliferate.
47	5.5	D	There continues to be a lack of specialized nanotech infrastructure and people in the state.
10	5.3	D	The amount of hype relative to success continues to grow.
40	5.0	D	Other regions of the country draw nanotech talent from the state.
1	4.9	D	A non-nanotech energy source is developed.
14	4.8	D	Texas chooses not to focus on a limited set of nanotechnologies.
41	4.7	D	Texas attempts to compete in areas in which other states have already established a monopoly.
31	4.2	D	The state continues to focus funding on old technologies.
38	3.9	D	Terrorism becomes an increasing problem.
33	3.7	D	Economic factors push nanotech manufacturing offshore.
53	3.5	D	Texas leaders fail to realize that nanotechnology is a global industry.
45	3.5	D	There continues to be a lack of "churn" and collaboration in the state's nanotech industry.