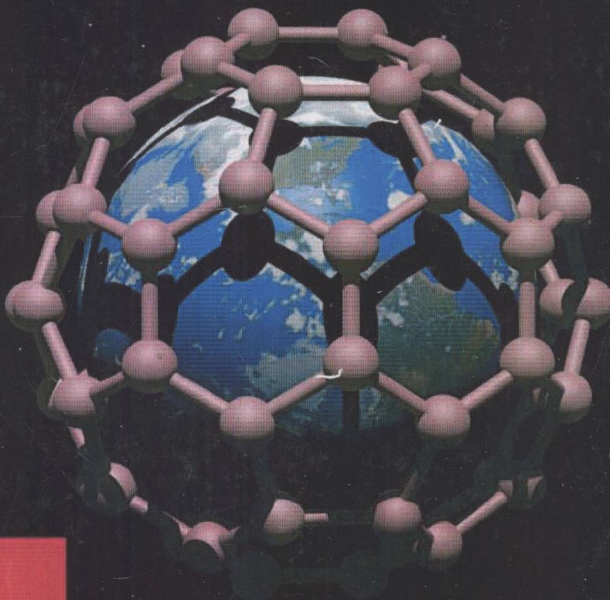
Foreword by Senators Joe Lieberman and George Allen



NANOTECHNOLOGY

Science, Innovation, and Opportunity

LYNN E. FOSTER

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PRENTICE
HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Library of Congress Cataloging-in-Publication Data

Foster, Lynn E.
Nanotechnology : science, innovation and opportunity / Lynn E. Foster.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-702575-0
1. Nanotechnology. 2. Nanotechnology--Social aspects. I. Title.
T174.7.F68 2005
620'.5—dc22

2005027597

ISBN: 0-13-702575-0
This product is printed digitally on demand.
Second printing, March 2006

Nanotechnology

Dedicated to Richard Feynman:
For having a vision of things smaller than any of us
and a spirit bigger than all of us.

And to my wife Miriam:
For enduring the vision of one man.

Foreword

When Congress passed and the President signed the 21st Century Nanotechnology Research and Development Act, or Public Law 108-153, in December 2003, our goal was to help spur and coordinate research and technology development in this exciting and promising area, one that has the potential to transform every aspect of our lives. By manipulating matter at a molecular scale, nanotechnology may allow us to develop new materials and devices that have unique properties beyond the realm of current conventional technology. Its potential economic effects are also profound, as some have estimated that its impact on both existing and new industries may easily exceed tens of billions of dollars by the end of this decade, and a trillion dollars not too many years beyond. Applications ranging from novel and highly targeted therapeutic treatments for diseases including cancer to such timely concerns as increased energy efficiency or tools for providing a cleaner environment certainly emphasize the potentially transformational nature of nanotechnology.

While many potential applications are some years ahead of us, the increasing frequency with which articles on nanotechnology are appearing in trade publications, investment publications, and in the mainstream media tell us that the science is already moving beyond the laboratory. Yet as we move ahead with the development of this frontier technology, it is important that we also pay attention to the issues beyond fundamental science and discovery that are equally important—issues such as technology innovation and technology transfer. And it is not just economic issues that need to be considered. As with any new technology, we need to pay careful attention to minimizing any potential impact on the environment as we move ahead. As the chapters in this book indicate, while much work lies ahead, we are making exciting progress in each of these areas.

Senator Joe Lieberman
Senator George Allen
Washington, D.C., November 2005

Preface

During the past century, human life spans have almost doubled, and travel and communication happen with an ease and speed that would have been considered science fiction only a few generations ago. Remarkably, the pace of innovation is actually increasing over that of the past.

Science has now advanced to the point that those on the cutting edge of research work with individual atoms and molecules. This is the defining characteristic of the new metafield of nanotechnology, which encompasses a broad range of both academic research and industrial development. At this small scale, the familiar classical physics guideposts of magnetism and electricity are no longer dominant; the interactions of individual atoms and molecules take over. At this level—roughly 100 nanometers (a nanometer being a billionth of a meter, and a human hair being 50,000 nanometers wide) and smaller—the applicable laws of physics shift as Newtonian yields to quantum.

Nanotechnology holds the promise of advances that exceed those achieved in recent decades in computers and biotechnology. Its applications will have dramatic infrastructural impacts, such as building tremendously faster computers, constructing lighter aircraft, finding cancerous tumors still invisible to the human eye, or generating vast amounts of energy from highly efficient solar cells. Nanotechnology will manifest in innovations both large and small in diverse industries, but the real benefit will accumulate in small cascades over decades rather than in a sudden, engulfing wave of change. It is not the "Next Big Thing" but rather will be any number of "next large things". Nanotechnology may not yield a result as dramatic as Edison's lightbulb but rather numerous gains as pervasive as the integrated-circuit-controlled lightbulbs in the traffic lights that are ubiquitous in modern life.

Although the lightbulb breakthroughs will be few, there will be numerous benefits taken for granted, such as the advantages that the automated intelligence of traffic grids provide to major cities. This should not be a surprise, because nanotechnology is not an invention but rather a range of fields of study and applications, defined by size, that use tools, ideas, and intuitions available to innumerable scientific disciplines. Thus nanotechnology offers tremendous potential for several key reasons. Materials and processes at that size have unique properties not seen at larger scale, offer proportionately greater reactive surface area than their larger counterparts, and can be used in or with living organisms for medical applications. As a result, familiar materials can have completely different properties at the nanoscale.

For example, carbon atoms form both coal and diamonds, but with different molecular arrangements. Scientists now know that carbon molecules at the nanoscale can form cylindrical tubes, called carbon nanotubes, that are much stronger than steel and conduct electricity, neither of which is possible with the carbon found in coal or diamonds. Carbon nanotubes may one day provide key breakthroughs in medicine and electronics. Likewise, nanotechnology can provide breakthroughs in industrial uses. The electrical current produced in solar cells or batteries reflects the flow of electrons from one surface to another. Nanotechnology has already enabled the demonstration of a vastly increased surface area of electrodes that allows electrons to flow much more freely, along with corresponding improvements in battery performance. Safer, cheaper, and cleaner electricity and electrical storage would obviously have a dramatic impact on our society.

Another reason nanotechnology holds so much promise is that it enables solutions at the same size scale as biological organisms, such as the individual cells in our bodies. Engineered materials are possible, such as ultrasmall particles made in the exact size to perform like a "smart bomb" in delivering drugs in the blood stream. Other applications might detect cancer when it is only a few cells in size. Future convergence of nanotechnology and biotechnology may combine biological and man-made devices in a variety of applications, such as batteries for implanted heart pacemakers that draw electrical current from the wearer's glucose rather than from surgically implanted batteries.

Yet another important facet of nanotechnology—one that underpins both its promise and the challenges—is that it embraces and attracts so many different disciplines that researchers and business leaders are working in, among them, chemistry, biology, materials science, physics, and computer science. Although each field has tremendously talented people, each also has its own somewhat unique training and terminology. Almost like the parable of the blind men and the elephant, each group approaches the molecular level with unique skills, training, and language. Communication and research between academic disciplines and between researchers and their business counterparts is critical to the advancement of nanotechnology.

With the diversity of professional cultures in mind, a central goal of this book is to promote communication and cooperation between researchers and industry by including similarly diverse articles written by experts but accessible to everyone.

The depth of scientific talent and the substantial resources being devoted to nanotechnology are a tremendous cause for optimism for both near-term and long-term gains. Ultimately nanotechnology will yield greater impact than information technology or biotechnology has. However, the tempo of technology is not set by the velocity of novel discoveries, but rather by the pace of what the market will embrace and pay for. The medium term in nanotechnology will be difficult and delayed by issues far beyond scientific research or product prototyping—namely, by the long, difficult process of new products gaining traction in the marketplace. To reach the stage of a viable product, the innovations will have to overcome issues such as how they are integrated, how much power they consume, and how they are controlled. Only then will the marketplace vote with dollars on the technology. For these reasons, another goal of this book is to highlight these issues so that a broader audience can address them with its respective understanding and resources.

This book is organized into four matrixed sections. Section One is focused on the history and development drivers of innovation. The first chapter highlights a historical example from the early days of the biotechnology industry as a cautionary lesson about a new industry developing with new tools and tremendous promise. The promise of nanotechnology to solve the world's energy problem is outlined in Chapter 2, along with the impact the solution would have on solving other problems as well. Chapter 3 is a discussion of the role played by expectations in the development of an industry.

Section Two focuses on the talents, roles, and motivations of the main players and individuals, along with the organizational factors that drive technologies forward or limit their impact. Chapter 4 presents the vision of a venture capitalist who takes a long-term view of nanotechnology as the nexus of disruptive innovation, and Chapter 5 outlines current investment decisions in nanotechnology. Chapter 6 outlines the U.S. government's role in funding research and establishing policies for the safe and effective use of nanotechnology. Then Chapter 7 discusses specific areas of academic research, and Chapter 8 explains how technologies developed there are brought to commercial use. The role of U.S. patent law in commerce follows in Chapter 9, with a discussion of its impact on the advance of nanotechnology. Chapter 10 explains why entrepreneurs are the key drivers of change in a new industry and help it advance by taking tremendous personal risks. Chapter 11 discusses the challenges within a large corporation that is developing technology products.

Finally, Chapter 12 presents an overview of technologies developed in federal laboratories and describes how they are commercialized.

Section Three considers specific areas of innovation: nanoscale materials (Chapter 13) as well as other areas where nanotechnology is making a dramatic impact: nano-enabled sensors (Chapter 14), the microelectronics industry (Chapter 15), and drug delivery (Chapter 16). This part concludes with a chapter (Chapter 17) specifically on the intersection of nanotechnology and biotechnology, a combination that holds enormous potential to impact medicine and health.

Section Four suggests that the convergence of science at the nanoscale foreshadows a transformation and revolutionary change in society (Chapter 18) and highlights ethical considerations in the advance of nanotechnology (Chapter 19).

The Epilogue features a prescient speech given in 1983 by the late Richard Feynman, the legendary physicist who first envisioned nanotechnology.

Working at the level of individual atoms and molecules allows researchers to develop innovations that will dramatically improve our lives. The new realm of nanotechnology holds the promise of improving our health, our industry, and our society in ways that exceed even those of computers or biotechnology.

Acknowledgments

These acknowledgments must begin with, and I cannot thank enough, distinguished scientist Dr. Hans Coufal of IBM and the Nanoelectronics Research Initiative for the inspiration and encouragement to undertake this project.

Innumerable thanks go to the many authors who contributed to this volume. The responsiveness and generosity of such a distinguished group of researchers and business professionals transformed the arduous task of bringing this book together into a particularly gratifying one. Special thanks are also due to Bernard Goodwin of Prentice Hall for his continuing guidance.

Behind my efforts is one person whose day-to-day patience and encouragement were essential: my wife, Miriam, who has shared the highs and lows of a consuming project. These few words are only a small fraction of my enormous sense of love, appreciation, and thanks.

Four people worked "above and beyond" on this book, and without their special behind-the-scenes efforts it would not have been completed: Michael Krieger of Williken Wilson Loh & Stris LLP, Geoff Holdridge, National Nanotechnology Coordination Office and WTEC, Inc., Matt Laudon of the Nano Science & Technology Institute, and Brent Segal of Nantero.

Thanks are due also to several people who contributed greatly to this book but were not listed as authors because of editorial constraints, in particular the following: Art Riggs, City of Hope's Beckman Research Institute; Howard Schmidt, Rice University; Amit Kenjale, Caltech; Robert Giasoli, XCOM Wireless and the Micro and Nanotechnology Commercialization Education Foundation; Jim Gimzewski, University of California, Los Angeles, and the California NanoSystems Institute; Michael Holton, Smart Technology Ventures; Jim Spohrer, IBM; Daniel Choi, NASA Jet Propulsion Lab; Marc Madou, University of California, Irvine; Peggy Arps, University of California, Irvine; Susan Zhou, University of California, Irvine; Tony Cheetham, University of California, Santa Barbara.

Numerous colleagues at Greenberg Traurig, LLP, were a source of information, ongoing support, and encouragement, as was the firm itself. My nanotechnology universe was broadened by the opportunity to do programs for the Caltech Enterprise Forum, and by the wisdom and camaraderie of many of its board members.

Thanks for the foundation of this book are due to Dr. Joe Lichtenhan of Hybrid Plastics, who started me on the nanotechnology road, and to Jerry Gallwas, Hans Coufal, Malcolm Green, and Sergeant Major (Retired) Peter Van Borkulo for being mentors to me for so many years. Special appreciation goes to Cheryl Albus of the National Science Foundation for her constructive skepticism that helped me separate substance from fad in nanotechnology.

Many others contributed greatly and are due wholehearted thanks for helping bring this book to completion: Kevin Ausman, Rice University; John Belk, The Boeing Company; Keith Boswell, Virginia Economic Development Partnership; Peter Burke, University of California, Irvine; Altaf Carim, U.S. Department of Energy; Scott Carter, Caltech; Gerard Diebner, Greenberg Traurig; Andre Dehon, Caltech; Alex Dickenson, Luxtera; Sverre Eng, NASA Jet Propulsion Lab (retired); David Forman, Small Times Media; Wayne Jones, Greenberg Traurig; Sam Gambhir, Stanford; Guanglu Ge, Caltech; Maurice Gell, University of Connecticut; Peter Gluck, Greenberg Traurig; Peter Grubstein, NGEN Partners; Joe Helble, Office of Senator Joseph Lieberman and Dartmouth College; Jamie Hjort, Office of Senator George Allen; Julie Holland, NASA Commercialization Center, California Polytechnic University; Robert Hwang, U.S. DOE Brookhaven National Laboratory; Srinivas Iyer, Los Alamos National Laboratory; Barbara Karn, U.S. Environmental Protection Agency; David Knight, Terbine, Inc.; David Lackner, NASA Ames; Tony Laviano, Loyola Marymount University; Tom Loo, Greenberg Traurig; Goran Matijasevic, University of California, Irvine; Paul McQuade, Greenberg Traurig; John Miller, Arrowhead Research; Brian Pierce, Rockwell Scientific; Andy Quintero, The Aerospace Corporation; Phil Reilly, Macusight, Inc.; Tony Ricco, Stanford; Bart Romanowicz, The Nano Science & Technology Institute; Ari Requicha, USC; Michael Roukes, Caltech; James Rudd, The National Science Foundation; Frank Sadler, Office of Senator George Allen; Carlos Sanchez, U.S. Army; John Sargent, U.S. Department of Commerce; Jeff Schloss, National Institutes of Health; Clayton Teague, National Nanotechnology Coordination Office; Jim Von Ehr, Zyvex; Kumar Wickramasinghe, IBM; Stan Williams, HP; Hiroshi Yokoyama, National Institute of Advanced Industrial Science and Technology, Japan; CJ Yu, Glyport, Inc.

—Lynn Foster
Los Angeles, July 2005

About the Author

Lynn E. Foster is the Emerging Technologies Director of Greenberg Traurig, LLP, one of the largest law firms in the United States. In this position he advises technology companies on technology transfer, patent licensing, strategic partnerships and raising capital.

Prior to joining Greenberg Traurig, Mr. Foster held technology industry positions in corporate, entrepreneurial, and government settings, among them managing software development in the aerospace industry, heading a startup, and managing a seed-stage commercialization grant program. He serves on Advisory Boards for the Nano Science and Technology Institute and the International Engineering Consortium, as well as the Executive Committee of the Caltech Enterprise Forum. He authored the first Nanotechnology Trade Study and has directed eight Nanotechnology conferences and trade missions. He also has 20 years of active and reserve service with the U.S. Army, including service in the first Gulf War and Bosnia. He holds an M.B.A. and a B.S. in production and operations management.

Contributors

Gerald Gallwas

Gerald Gallwas was a member of the original team in the mid-1960s that founded and managed the growth of what became the clinical diagnostic business of Beckman Instruments. The team pioneered a new technology based on kinetic rate measurements applied to first-order chemical reactions for clinically significant blood constituents.

As the business grew, he served in many roles, from new product development to directing clinical field trials in the United States, Europe, and Japan. This led to extensive involvement with professional and trade organizations as well as regulatory agencies. He retired after 30 years of service as Director of Program Management, overseeing multimillion-dollar new product development programs. Since that time, he has consulted widely in the United States and Europe on new product development, strategic and business planning, organizational development, and marketing. Gallwas holds a B.S. in chemistry from San Diego State University.

Richard Smalley

Nobel Laureate Richard E. Smalley received his B.S. in 1965 from the University of Michigan. After an intervening four-year period in industry as a research chemist with Shell, he earned his M.S. in 1971 from Princeton University and his Ph.D. in 1973. During a postdoctoral period with Lennard Wharton and Donald Levy at the University of Chicago, Smalley pioneered what has become one of the most powerful techniques in chemical physics: supersonic beam laser spectroscopy. After coming to Rice University in 1976 he was named to the Gene and Norman Hackerman Chair in Chemistry in 1982. He was a founder of the Rice Quantum Institute in 1979 and served as the Chairman from 1986 to 1996. In 1990 he became a professor in the

Department of Physics and was appointed University Professor in 2002. He was the founding director of the Center for Nanoscale Science and Technology at Rice from 1996 to 2002, and is now Director of the new Carbon Nanotechnology Laboratory at Rice.

In 1990 he was elected to the National Academy of Sciences, and in 1991 to the American Academy of Arts and Sciences. He is the recipient of the 1991 Irving Langmuir Prize in Chemical Physics, the 1992 International Prize for New Materials, the 1992 E.O. Lawrence Award of the U.S. Department of Energy, the 1992 Robert A. Welch Award in Chemistry, the 1993 William H. Nichols Medal of the American Chemical Society, the 1993 John Scott Award of the City of Philadelphia, the 1994 Europhysics Prize, the 1994 Harrison Howe Award, the 1995 Madison Marshall Award, the 1996 Franklin Medal, the 1996 Nobel Prize in Chemistry, the Distinguished Public Service Medal awarded by the U.S. Department of the Navy in 1997, the 2002 Glenn T. Seaborg Medal, and the 2003 Lifetime Achievement Award of *Small Times* magazine. He received three honorary degrees in 2004: an Honorary Doctorate from the University of Richmond; a Doctor Scientiarum Honoris Causa from Technion Israel Institute of Technology, and a Doctor of Science from Tuskegee University.

Smalley is widely known for the discovery and characterization of C60 (Buckminsterfullerene, aka the "buckyball"), a soccer ball–shaped molecule that, together with other fullerenes such as C70, now constitutes the third elemental form of carbon (after graphite and diamond). His current research is on buckytubes: elongated fullerenes that are essentially a new high-tech polymer, following on from nylon, polypropylene, and Kevlar. But unlike any of these previous wonder polymers, these new buckytubes conduct electricity. They are likely to find applications in nearly every technology where electrons flow. In February 2000 this research led to the start up of a new company, Carbon Nanotechnologies, Inc., which is now developing large-scale production and applications of these miraculous buckytubes.

Peter Coffee

Peter Coffee is Technology Editor of *eWEEK*, Ziff Davis Media's national news magazine of enterprise infrastructure. He has twenty years' experience in evaluating information technologies and practices as a developer, consultant, educator, and internationally published author and industry analyst.

Coffee writes product reviews, technical analyses, and his weekly "Epicenters" column on disruptive forces in IT tools and practices; he has appeared on CBS, NBC, CNN, Fox, and PBS newscasts addressing Internet security, the Microsoft antitrust case, wireless telecom policies, and other e-business issues. He chaired the four-day Web Security Summit conference in Boston during the summer of 2000 and has been a keynote speaker or moderator at technical conferences throughout the United States and in England. His most recent book is *Peter Coffee Teaches PCs*, published in 1998 by Que; he previously authored Que's ZD Press tutorial, "How to Program Java." He played a lead role in developing *eWEEK* Labs' 2001 series of special reports titled "Five Steps to Enterprise Security." His current *eWEEK* beats include development tools and business intelligence products.

Before joining *eWEEK* (then called *PC Week*) full time in 1989, Coffee held technical and management positions at Exxon and The Aerospace Corporation, dealing with chemical facility project control, Arctic project development, strategic defense analysis, end-user computing planning and support, and artificial intelligence applications research. He has been one of *eWEEK*'s lead analysts throughout the life cycles of technologies, including x86 and RISC microprocessors; Windows, OS/2, and Mac OS; object technologies, including Smalltalk, C++, and Java; and security technologies including strong encryption. He holds an engineering degree from MIT and an M.B.A. from Pepperdine University and has taught classes in the Department of Computer Science at UCLA and at Pepperdine's Graziadio School of Business and Management and the Chapman College School of Business. His weekly newsletter, *Peter Coffee's Enterprise IT Advantage*, and his other writings are available at www.eweek.com/petercoffee.

Steve Jurvetson

Steve Jurvetson is a Managing Director of Draper Fisher Jurvetson (DFJ.com). He was the founding VC investor in Hotmail (MSFT), Interwoven (IWOV), and Kana (KANA). He also led the firm's investments in Tradex and Cyras (acquired by Ariba and Ciena for $8 billion) and, most recently, in pioneering companies in nanotechnology and molecular electronics. Previously, Jurvetson was an R&D Engineer at Hewlett-Packard, where seven of his communications chip designs were fabricated. His prior technical experience also includes programming, materials science research (TEM atomic imaging of GaAs) and computer design at HP's PC Division, the Center for Materials Research, and Mostek. He has also worked in product marketing at Apple and NeXT Software.

At Stanford University, he finished his B.S.E.E. in two and a half years and graduated first in his class, as the Henry Ford Scholar. Jurvetson also holds an M.S. in electrical engineering from Stanford. He received his M.B.A.

from the Stanford Business School, where he was an Arjay Miller Scholar. Jurvetson also serves on the Merrill Lynch and STVP advisory boards and is Co-Chair of the NanoBusiness Alliance. He was honored as "The Valley's Sharpest VC" on the cover of *Business 2.0* and was chosen by the *San Francisco Chronicle* and *San Francisco Examiner* as one of "the ten people expected to have the greatest impact on the Bay Area in the early part of the 21st Century." He was profiled in the *New York Times Magazine* and featured on the cover of *Worth* and *Fortune* magazines. He was chosen by *Forbes* as one of "Tech's Best Venture Investors," by the *VC Journal* as one of the "Ten Most Influential VCs," and by *Fortune* as part of its "Brain Trust of Top Ten Minds."

Daniel V. Leff

Prior to joining Harris & Harris Group, Leff was a Senior Associate with Sevin Rosen Funds in the firm's Dallas, Texas, office, where he focused on early-stage investment opportunities in semiconductors, components, and various emerging technology areas. While at Sevin Rosen Funds, he played an integral role in the funding of Nanomix, InnovaLight, Sana Security, and D2Audio. Leff has also worked for Redpoint Ventures in the firm's Los Angeles office. In addition, he previously held engineering, marketing, and strategic investment positions with Intel Corporation.

Leff received his Ph.D. in physical chemistry from UCLA's Department of Chemistry and Biochemistry, where his thesis adviser was Professor James R. Heath (recipient of the 2000 Feynman Prize in Nanotechnology). Leff also received a B.S. in chemistry from the University of California, Berkeley, and an M.B.A. from The Anderson School at UCLA, where he was an Anderson Venture Fellow. Leff has published several articles in peer-reviewed scientific journals and has been awarded two patents in the field of nanotechnology. He is also a member of the business advisory boards of the NanoBusiness Alliance and the California NanoSystems Institute (CNSI).

R. Douglas Moffat

R. Douglas Moffat, CFA, is President of Moffat Capital, LLC, and Nanotech Financing Solutions, LLC. Moffat Capital, LLC, is a broker/dealer experienced in raising private capital, and Nanotech Financing Solutions, LLC, is a leading consultancy in this emerging field.

Moffat has 30 years' experience as a research analyst at leading Wall Street brokerage firms and has broad experience in industrial markets. He published research on the metals and steel industries, diversified industrial