1 Introducing Nano

Nanotechnology is truly a portal opening on a new world.

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In this chapter…

WHY DO I CARE ABOUT NANO? . . . .

Over the past few years, a little word with big potential has been rapidly insinuating itself into the world's consciousness. That word is "nano." It has conjured up speculation about a seismic shift in almost every aspect of science and engineering with implications for ethics, economics, international relations, day-to-day life, and even humanity's conception of its place in the universe. Visionaries tout it as the panacea for all our woes. Alarmists see it as the next step in biological and chemical warfare or, in extreme cases, as the opportunity for people to create the species that will ultimately replace humanity.

While some of these views are farfetched, nano seems to stir up popular, political, and media debate in the same way that space travel and the Internet did in their respective heydays. The federal government spent more than $422 million on nano research in 2001. In 2002, it is scheduled to spend more than $600 million on nano programs, even though the requested budget was only $519 million, making nano possibly the only federal program to be awarded more money than was requested during a period of general economic distress. Nano is also among the only growth sectors in federal spending not exclusively related to defense or counterterrorism, though it does have major implications for national security.

Federal money for nano comes from groups as diverse as the National Science Foundation, the Department of Justice, the National Institutes for Health, the Department of Defense, the Environmental Protection Agency, and an alphabet soup of other government agencies and departments. Nano's almost universal appeal is indicated by the fact that it has political support from both sides of the aisle—Senator Joseph Lieberman and former Speaker-of-the-House Newt Gingrich are two of nano's most vocal promoters, and the National Nanotechnology Initiative (NNI) is one of the few Clinton-era programs strongly backed by the Bush administration.

The U.S. government isn't the only organization making nano a priority. Dozens of major universities across the world—from Northwestern University in the United States to Delft University of Technology in the Netherlands and the National Nanoscience Center in Beijing, China—are building new faculties, facilities, and research groups for nano. Nano research also crosses scientific disciplines.

Chemists, biologists, doctors, physicists, engineers, and computer scientists are all intimately involved in nano development.

Nano is big business. The National Science Foundation predicts that nano-related goods and services could be a $1 trillion market by 2015, making it not only one of the fastest-growing industries in history but also larger than the combined telecommunications and information technology industries at the beginning of the technology boom in 1998. Nano is already a priority for technology companies like HP, NEC, and IBM, all of whom have developed massive research capabilities for studying and developing nano devices. Despite this impressive lineup, well-recognized abbreviations are not the only organizations that can play. A host of start-ups and smaller concerns are jumping into the nano game as well. Specialty venture capital funds, trade shows, and periodicals are emerging to support them. Industry experts predict that private equity spending on nano could be more than $1 billion in 2002. There is even a stock index of public companies working on nano.

In the media, nano has captured headlines at CNN, MSNBC, and almost every online technical, scientific, and medical journal. The Nobel Prize has been awarded several times for nano research, and the Feynman Prize was created to recognize the accomplishments of nanoscientists. *Science* magazine named a nano development as Breakthrough of the Year in 2001, and nano made the cover of *Forbes* the same year, subtitled "The Next Big Idea." Nano has hit the pages of such futurist publications as *Wired Magazine*, found its way into science fiction, and been the theme of episodes of *Star Trek: The Next Generation* and *The X-Files* as well as a one-liner in the movie *Spiderman*.

In the midst of all this buzz and activity, nano has moved from the world of the future to the world of the present. Innovations in nano-related fields have already sparked a flurry of commercial inventions from faster-burning rocket fuel additives to new cancer treatments and remarkably accurate and simple-to-use detectors for biotoxins such as anthrax. Nano skin creams and suntan lotions are already on the market, and nano-enhanced tennis balls that bounce longer appeared at the 2002 Davis Cup. To date, most companies that claim to be nano companies are engaging in research or trying to cash in on hype rather than working toward delivering a true nano product, but there certainly are exceptions. There is no shortage of opinions on where nano can go and what it can mean, but both pundits and critics agree on one point—no matter who you are and what your business and interests may be, this science and its spin-off technologies have the potential to affect you greatly.

There are also many rumors and misconceptions about nano. Nano isn't just about tiny little robots that may or may not take over the world. At its core, it is a great step forward for science. NNI is already calling it "The Next Industrial Revolution"—a phrase they have imprinted on a surface smaller than the width of a human hair in letters 50 nanometers wide. (See Figure 1.1.)

For the debate on nano to be a fruitful one, everyone must know a little bit about what nano is. This book will address that goal, survey the state of the art, and offer some thoughts as to where nano will head in the next few years.

WHO SHOULD READ THIS BOOK? . . . .

This book is designed to be an introduction to the exciting fields of nanotechnology and nanoscience for the nonscientist. It is aimed squarely at the professional reader who has been hearing the buzz about nano and wants to know what it's all about. It is chiefly concerned with the science, technology, implications, and future of nano, but some of the business and financial aspects are covered briefly as well. All the science required to understand the book is reviewed in Chapter 3. If you have taken a high school or college chemistry or physics class, you will be on familiar ground.

We have tried to keep the text short and to the point with references to external sources in case you want to dig deeper into the subjects that interest you most. We have also tried to provide the essential vocabulary to help you understand what you read in the media and trade press coverage of nano while keeping this text approachable and easy to read. We've highlighted key terms where they are first defined and included a glossary at the end.

We hope that this book will be a quick airplane or poolside read that will pique your interest in nano and allow you to discuss nano

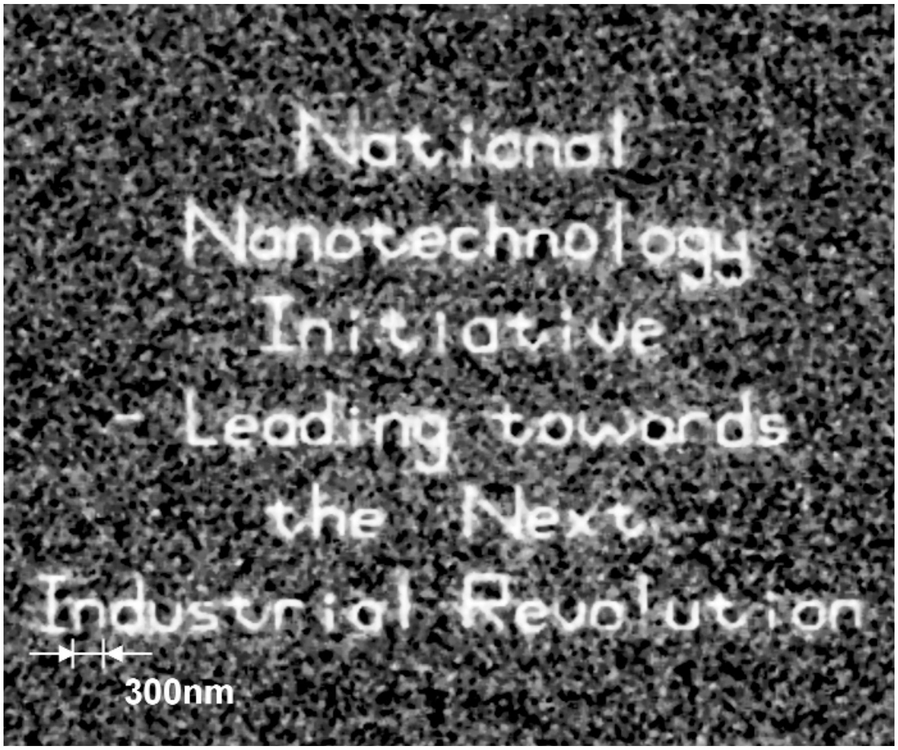

Figure 1.1
The Next Industrial Revolution, an image of a nanostructure. *Courtesy of the Mirkin Group, Northwestern University.*

with your friends and fascinate the guests at your next dinner party. Nano will be at the center of science, technology, and business for the next few years, so everyone should know a bit about it. We have designed this book to get you started. Enjoy!

WHAT IS NANO? A DEFINITION . . . .

When Neil Armstrong stepped onto the moon, he called it a small step for man and a giant leap for mankind. Nano may represent another giant leap for mankind, but with a step so small that it makes Neil Armstrong look the size of a solar system.

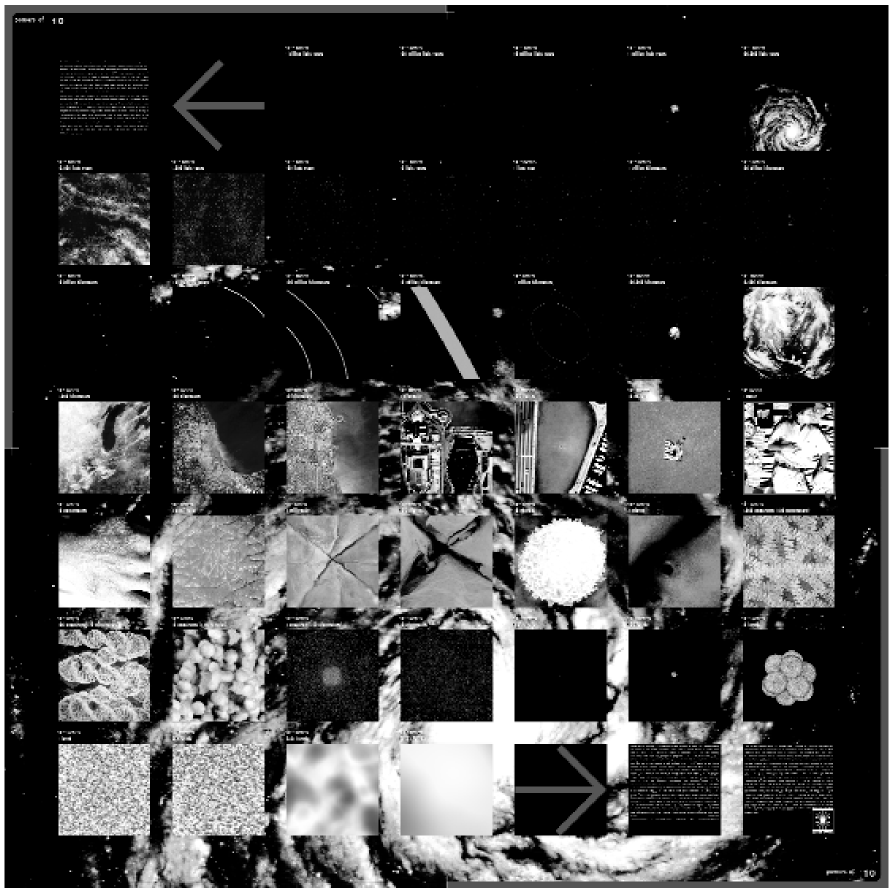

Figure 1.2
This image shows the size of the nanoscale relative to some things we are more familiar with. Each image is magnified 10 times from the image before it. As you can see, the size difference between a nanometer and a person is roughly the same as the size difference between a person and the orbit of the moon. © 2001 Lucia Eames/Eames Office (www.eamesoffice.com).

The prefix "nano" means one billionth. One nanometer (abbreviated as 1 nm) is 1/1,000,000,000 of a meter, which is close to 1/1,000,000,000 of a yard. To get a sense of the nano scale, a human hair measures 50,000 nanometers across, a bacterial cell measures a few hundred nanometers across, and the smallest features that are commonly etched on a commercial microchip as of February 2002 are around 130 nanometers across. The smallest things seeable with the unaided human eye are 10,000 nanometers across. Just ten hydrogen atoms in a line make up one nanometer. It's really very small indeed. See Figure 1.2.

Nanoscience is, at its simplest, the study of the fundamental principles of molecules and structures with at least one dimension roughly between 1 and 100 nanometers. These structures are known, perhaps uncreatively, as *nanostructures*. *Nanotechnology* is the application of these nanostructures into useful *nanoscale* devices. That isn't a very sexy or fulfilling definition, and it is certainly not one that seems to explain the hoopla. To explain that, it's important to understand that the nanoscale isn't just small, it's a special kind of small.

Anything smaller than a nanometer in size is just a loose atom or small molecule floating in space as a little dilute speck of vapor. So nanostructures aren't just smaller than anything we've made before, they are the smallest solid things it is possible to make. Additionally, the nanoscale is unique because it is the size scale where the familiar day-to-day properties of materials like conductivity, hardness, or melting point meet the more exotic properties of the atomic and molecular world such as wave-particle duality and quantum effects. At the nanoscale, the most fundamental properties of materials and machines depend on their size in a way they don't at any other scale. For example, a nanoscale wire or circuit component does not necessarily obey Ohm's law, the venerable equation that is the foundation of modern electronics. Ohm's law relates current, voltage, and resistance, but it depends on the concept of electrons flowing down a wire like water down a river, which they cannot do if a wire is just one atom wide and the electrons need to traverse it one by one. This coupling of size with the most fundamental chemical, electrical, and physical properties of materials is key to all nanoscience. A good and concise definition of nanoscience and nanotechnology that captures the special properties of the nanoscale comes from a National Science Foundation document edited by Mike Roco and issued in 2001:

> One nanometer (one billionth of a meter) is a magical point on the dimensional scale. Nanostructures are at the confluence of the smallest of human-made devices and the largest molecules of living things. Nanoscale science and engineering here refer to the fundamental understanding and resulting technological advances arising from the exploitation of new physical, chemical and biological properties of systems that are intermediate in size, between isolated atoms and molecules and bulk materials, where the transitional properties between the two limits can be controlled.

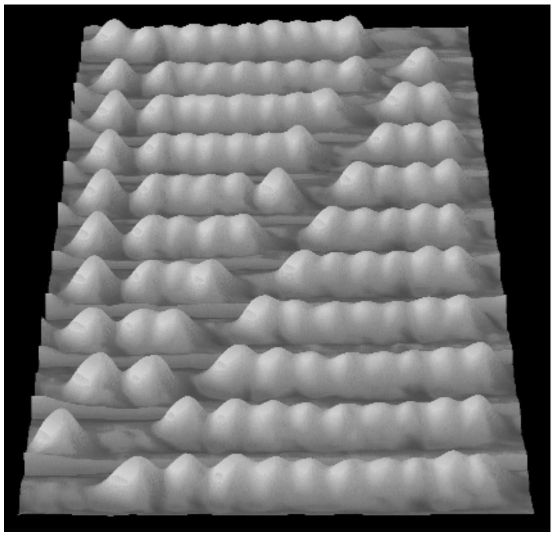

Figure 1.3
The nanoscale abacus. The individual bumps are molecules of carbon-60, which are about 1 nanometer wide. *Courtesy of J. Gimzewski, UCLA.*

Although both fields deal with very small things, nanotechnology should not be confused with its sister field, which is even more of a mouthful—microelectromechanical systems (*MEMS*). MEMS scientists and engineers are interested in very small robots with manipulator arms that can do things like flow through the bloodstream, deliver drugs, and repair tissue. These tiny robots could also have a host of other applications including manufacturing, assembling, and repairing larger systems. MEMS is already used in triggering mechanisms for automobile airbags as well as other applications. But while MEMS does have some crossover with nanotechnology, they are by no means the same. For one thing, MEMS is concerned with structures between 1,000 and 1,000,000 nanometers, much bigger than the nanoscale. See Figure 1.3. Further, nanoscience and nanotechnology are concerned with all properties of structures on the nanoscale, whether they are chemical, physical, quantum, or mechanical. It is more diverse and stretches into dozens of subfields. Nanotech is not nanobots.

In the next few chapters, we'll look in more depth at the "magical point on the dimensional scale," offer a quick recap of some of the basic science involved, and then do a grand tour of nanotech's many faces and possibilities.

A NOTE ON MEASURES . . . .

Almost all nanoscience is discussed using SI (mostly metric) measurement units. This may not be instinctive to readers brought up in the American system and not all the smaller measurements are frequently used. A quick list of small metric measures follows to help set the scale as we move forward into the world of the very small.

SI Unit (abbreviation)	Description
meter (m)	Approximately three feet or one yard
centimeter (cm)	1/100 of a meter, around half an inch
millimeter (mm)	1/1,000 of a meter
micrometer (μm)	1/1,000,000 of a meter; also called a micron, this is the scale of most integrated circuits and MEMS devices
nanometer (nm)	1/1,000,000,000 of a meter; the size scale of single small molecules and nanotechnology