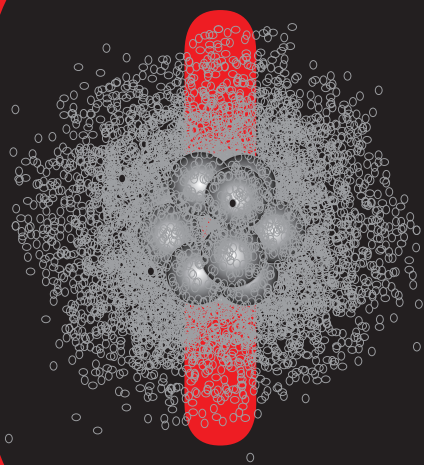
Ben Rogers | Jesse Adams | Sumita Pennathur

Nano

NANOTECHNOLOGY
THE WHOLE STORY



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Preface

We did not want this to be a book that glosses over the nitty-gritty stuff, assuming you already know everything, nor a book that uses "hand waving" to magically skirt around real explanations of the complex stuff. The tone of the book is intended to make it more readable—which is to say that it is not "textbook-y." Not stodgy.

This book is about nanotechnology, a gigantic topic about small things. It is a book that is intended to excite, inspire, and challenge you. We want to uncover the most important things about nanotechnology and give you the tools you need to dig deeper on your own. We want you to enjoy learning (maybe even laugh) and for you to find out a lot in a short time. There will be plenty of rigorous scientific support, but concepts will be conveyed in clear, simple language that you can digest and apply immediately. We do "A Little More" calculations together throughout the process so that you get a good feeling for the numbers of nanotechnology.

Nanotechnology represents a convergence of many sciences and technologies at the nanometer scale. In fact, it is becoming its own discipline altogether. It requires the ability to apply various scientific principles to system-level design and analysis. The multidisciplinary nature of nanotechnology—which draws from physics, chemistry, biology, and engineering—has the inherent challenge of educating people from all backgrounds.

We start with an overview treatment of nanotechnology, with special emphasis on the history, key personalities, and early milestones. Then on to the issues, promises, and fundamentals of nanotechnology. In fact, Chapter 1, "Big Picture of the Small World," stands alone as a comprehensive introduction, intended to answer your first questions as to what nanotechnology really is and could be. This chapter includes a discussion of the effects this new industry could have on human life, careers, education, and the environment.

Chapter 2 discusses scaling laws, giving us intuition about the physical ramifications of miniaturization. (While we think this is a useful chapter, be warned that it could bore you. If so, feel free to skip or skim it and use it as a reference.)

Then we dive headlong into nanotechnology. We begin with an "Introduction to Nanoscale Physics" (Chapter 3). Then we tackle the eight main disciplines: "Nanomaterials" (Chapter 4), "Nanomechanics" (Chapter 5), "Nanoelectronics" (Chapter 6), "Nanoscale Heat Transfer" (Chapter 7), "Nanophotonics" (Chapter 8), "Nanoscale Fluid Mechanics" (Chapter 9), "Nanobiotechnology" (Chapter 10), and "Nanomedicine" (Chapter 11). In these "nano" chapters, we provide the specific, fundamental differences between macroscale and nanoscale phenomena and devices, using applications to teach key concepts.

Welcome!

Enjoy!

Acknowledgments

For their help in bringing this book to life, the authors thank the National Science Foundation, Melodi Rodrigue, David Bennum, Jonathan Weinstein, Joe Cline, Jeff LaCombe, Michael Hagerman, Seyfollah Maleki, Palma Catravas, Roop Mahajan, Frank Kreith, Daniel Fletcher, Katherine Chen, Todd Sulchek, Nevada Nanotech Systems, Inc., Nevada Ventures, Robb Smith, Stuart Feigin, Chris Howard, Ian Rogoff, Ralph Whitten, David Burns, and the University of Nevada, Reno—especially the Library Department, the College of Engineering, and the Department of Mechanical Engineering.

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Ben Rogers

I would like to thank my two Tonys and my daughter Zofia for their undying love and support, and for allowing me the opportunity to be part of this work. Additionally, I thank all my educators as well as my students throughout the years for giving me the guidance and motivation to create such a textbook.

Sumita Pennathur

Thanks to all my family, friends, and mentors. You are all the best and this is dedicated to your hard work.

Jesse Adams

An Invitation

One more thing. We put a lot of work into making this book useful for you. So we invite every reader to comment on this book and tell us how we can make it even better. We want your suggestions for future editions and corrections to any errors you may discover. Please e-mail suggestions, questions, comments, and corrections to: michael.slaughter@taylorandfrancis.com. We plan to list the names of helpful readers in the Acknowledgments section of future editions of this book.

Here are those who have already contributed: Ongi Englander, Ed Hodkin, Morteza Mahmoudi, Aaron S. Belsh, Eva Wu, Brett Pearson, John C. Bean, Darryl Wu, Lia Hankla, Alec Hendricks, and the Davidson Academy.

That said, let us get started.

Authors

Ben Rogers is a writer and an engineer (BS 2001; MS 2002, University of Nevada, Reno). He has done research at Nanogen, the Oak Ridge National Laboratory, and NASA's Jet Propulsion Laboratory, and published many technical papers, as well as fictional works and essays (which can be found at http://www.readrogers.com). He is currently the principal engineer at NevadaNano.

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1

Big Picture of the Small World

Nanotechnology means putting to use the unique physical properties of atoms, molecules, and other things measuring roughly 0.1–1000 nanometers. We are talking about engineering the smallest-ever structures, devices, and systems.

Nanotechnology is also a promise. A big one. Nobel laureates, novelists, and news anchors alike tell us on a daily basis that nanotechnology will completely change the way we live. They have promised us microscopic, cancer-eating robots swimming through our veins! Self-cleaning glass! Digital threads! Electronic paper! Palm-sized satellites! The cure for deafness! Molecular electronics! Smart dust! What the heck *is* smart dust—and when can we get our hands on some? A promise is a promise…

Such things are actually down the road. Nanotechnology has been hyped by techies who cannot wait to order a wristwatch with the entire Library of Congress stored inside, while others bespeak the hysteria of rapidly self-replicating gray goo. Much that is *nano* is burdened with overexpectations and misunderstanding. As usual, the reality lives somewhere between such extremes. Nanotechnology is like all technological development: inevitable. It is not so much a matter of what remains to be seen; the fun question is: Who will see it? Will we? Will our children? Their children? Turns out, we will all get to see some. Nanotechnology is already changing the way we live, and it is just getting started.

The nano from which this relatively new field derives its name is a prefix denoting 10^{-9}. *Nano* comes from *nanos*, a Greek word meaning "dwarf." In the case of nanotechnology, it refers to things in the ballpark of one-billionth of a meter in size. When Albert Einstein was in graduate school in 1905, he took experimental data on the diffusion of sugar in water and showed that a single sugar molecule is about 1 nm in diameter. Prefixes can be applied to any unit of the International System of Units (SI) to give multiples of that unit. Some of the most common prefixes for the various powers of 10 are listed in Table 1.1.

The word *nanotechnology* was first used in 1974 by Norio Taniguchi in a paper titled "On the Basic Concept of Nano-Technology" (with a hyphen). He wrote:

TABLE 1.1 Some Prefixes for SI Units

Yotta (Y)	10^{24}	1 septillion
Zetta (Z)	10^{21}	1 sextillion
Exa (E)	10^{18}	1 quintillion
Peta (P)	10^{15}	1 quadrillion
Tera (T)	10^{12}	1 trillion
Giga (G)	10^{9}	1 billion
Mega (M)	10^{6}	1 million
Kilo (k)	10^{3}	1 thousand
Hecto (h)	10^{2}	1 hundred
Deka (da)	10	1 ten
Deci (d)	10^{-1}	1 tenth
Centi (c)	10^{-2}	1 hundredth
Milli (m)	10^{-3}	1 thousandth
Micro (μ)	10^{-6}	1 millionth
Nano (n)	10^{-9}	1 billionth
Pico (p)	10^{-12}	1 trillionth
Femto (f)	10^{-15}	1 quadrillionth
Atto (a)	10^{-18}	1 quintillionth
Zepto (z)	10^{-21}	1 sextillionth
Yocto (y)	10^{-24}	1 septillionth

> In the processing of materials, the smallest bit size of stock removal, accretion or flow of materials is probably of one atom or one molecule, namely 0.1–0.2 nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm…. "Nano-technology" mainly consists of the processing … separation, consolidation and deformation of materials by one atom or one molecule.

By the 1980s, people were regularly using and spreading the word *nanotechnology.*

The late Richard Smalley (Figure 1.1), who shared the 1996 Nobel Prize in Chemistry with Harry Kroto and Robert Curl, was a champion of the nanotech cause. In 1999 he told Congress that "the impact of nanotechnology on the health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering and manmade polymers." Many scientists share Smalley's bullish assessment.

Nanotechnology has ambitiously been called the next industrial revolution, a wholly different approach to the way human beings rearrange matter. People have always tinkered with what the Earth has to

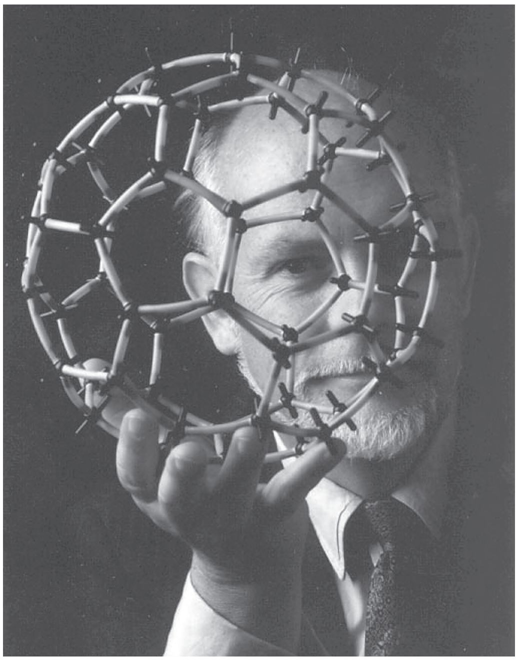

FIGURE 1.1 Richard Smalley. Until 1985, graphite and diamond were believed the only naturally occurring forms of carbon. Then Dr. Smalley, Harold Kroto, James Heath, Sean O'Brien, and Robert Curl discovered another one. It was a soccer ball–type arrangement they called *buckminsterfullerenes* (buckyballs, for short) after Richard Buckminster Fuller, the renowned architect credited with popularizing the geodesic dome. Similar molecules were soon discovered, including nanotubes. These new forms of carbon are called fullerenes. (Photo used with permission of Dr. Richard E. Smalley and Rice University.)

offer—there is nothing else with which to work. Technology is in many respects just the rearrangement of chunks of the Earth to suit our needs and our wants. And the Earth is nothing more than atoms. Ever since we dwelled in caves, we have put atoms over fires to heat them, bashed them against rocks to regroup them, and swallowed them for lunch. We just did not know about them, and we certainly could not see them, or control them one at a time.

Those days are over.

1.1 Understanding the Atom: Ex Nihilo Nihil Fit

If we slice a block of gold in two, it is still gold. Halve it again, and again, and again—still gold. But how many times can we divide the chunk and still have gold? And is it made up of *only* gold, or is there also empty space in the block?

In the fifth century BC, Greek philosophers Democritus (Figure 1.2) and his teacher, Leucippus, were asking questions like these. They posited that all matter was composed of undividable particles called *atomos*, which in Greek means "unbreakable" or "not sliceable." These particles were completely solid, homogeneous, and varied in size, shape, and weight. Between the atoms was void, Democritus said. The famous expression *ex nihilo nihil fit* (nothing comes from nothing) was his. Although he is credited with writing about 60 books on his theories, none survived.

A LITTLE MORE

Democritus said matter was composed of undividable particles called *atomos*, Greek for "unbreakable." Was he right?

No, atoms are indeed divisible; however, to split one is a messy endeavor, and they do not stay divided for long. A process of splitting atoms into smaller pieces is nuclear fission. This process releases tremendous amounts of energy—used in nuclear weapons and nuclear power generation.

Okay, so if atoms can be broken down into smaller parts, will picotechnology and femtotechnology be next?

During fission (and fusion also), certain subatomic particles are released but stable atoms are reformed immediately. Subatomic things—neutrons, protons, electrons—are of great consequence, and as our level of understanding about them deepens, entirely new technological possibilities will emerge. Still, picotechnology and femtotechnology do not make sense in the way that nanotechnology does. The nanoscale is the realm of the atom. With today's technology, you cannot build anything that lasts with smaller stuff. Atoms represent a fundamental frontier. Nanotechnology is not just another step in an ongoing technological trend toward miniaturization. We have reached a boundary.

Plato (ca. 427–347 BC) and Aristotle (384–322 BC) disagreed with the atom idea and stuck with the prevailing belief that all matter was composed of the four basic elements: earth, water, air, and fire. Epicurus (341–270 BC), however, adopted "atomism" as the foundation of his teachings and wrote hundreds of books on the topic. These, like Democritus' works, were lost. But the idea was not, and a Roman named Titus Lucretius Carus (96–55 BC) wrote poetry extolling atomism. These writings were unpopular with the Romans and later considered atheistic by many Christians. Carus' books of poetry, unlike the writings of his predecessors, were saved and passed on. French philosopher Pierre sample content of Nanotechnology: The Whole Story