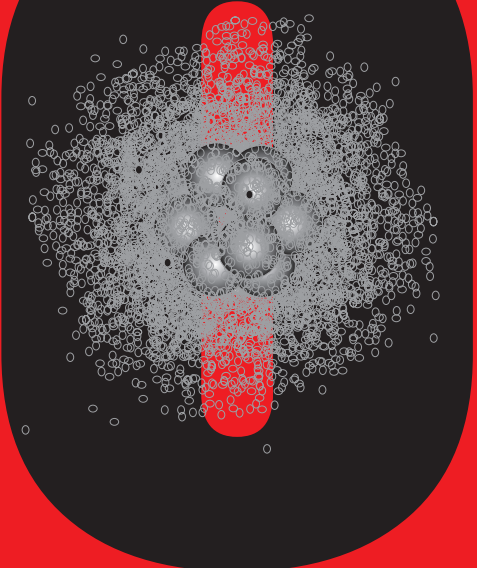


Ben Rogers | Jesse Adams | Sumita Pennathur

NSA

**NANOTECHNOLOGY
THE WHOLE STORY**

no



NANOTECHNOLOGY THE WHOLE STORY

Ben Rogers | Jesse Adams | Sumita Pennathur

NANOTECHNOLOGY THE WHOLE STORY



CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2013 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Version Date: 20121210

International Standard Book Number-13: 978-1-4665-0210-9 (eBook - PDF)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface	xiii
Acknowledgments	xv
An Invitation	xvi
Authors	xvii
1. Big Picture of the Small World	1
1.1 Understanding the Atom: Ex Nihilo Nihil Fit	3
1.2 Nanotechnology Starts with a Dare: Feynman's Big Little Challenges	11
1.3 Why One-Billionth of a Meter Is a Big Deal	15
1.4 Thinking It Through: The Broad Implications of Nanotechnology	18
1.4.1 Gray Goo	21
1.4.2 Environmental Impact	21
1.4.3 The Written Word	23
1.5 The Business of Nanotech: Plenty of Room at the Bottom Line, Too	25
1.5.1 Products	27
Recommendations for Further Reading	27
2. Introduction to Miniaturization	29
2.1 Background: The Smaller, the Better	29
2.2 Scaling Laws	30
2.2.1 The Elephant and the Flea	30
2.2.2 Scaling in Mechanics	34
2.2.3 Scaling in Electricity and Electromagnetism	37
2.2.4 Scaling in Optics	38
2.2.5 Scaling in Heat Transfer	41
2.2.6 Scaling in Fluids	42
2.2.7 Scaling in Biology	43
2.3 Accuracy of the Scaling Laws	44
Recommendations for Further Reading	46

3. Introduction to Nanoscale Physics	47
3.1 Background: Newton Never Saw a Nanotube	47
3.2 One Hundred Hours and Eight Minutes of Nanoscale Physics	47
3.3 The Basics of Quantum Mechanics	48
3.3.1 Atomic Orbitals (Not Orbits)	49
3.3.2 Electromagnetic Waves	52
3.3.2.1 How Electromagnetic Waves Are Made	56
3.3.3 The Quantization of Energy	57
3.3.4 Atomic Spectra and Discreteness	61
3.3.5 The Photoelectric Effect	61
3.3.6 Wave–Particle Duality: The Double-Slit Experiment	66
3.3.6.1 Bullets	67
3.3.6.2 Water Waves	68
3.3.6.3 Electrons	69
3.3.7 The Uncertainty Principle	71
3.3.8 Particle in a Well	73
3.4 Summary	76
Recommendations for Further Reading	77
4. Nanomaterials	79
4.1 Background: Matter Matters	79
4.2 Bonding Atoms to Make Molecules and Solids	79
4.2.1 Ionic Bonding	81
4.2.2 Covalent Bonding	83
4.2.3 Metallic Bonding	84
4.2.4 Walking through Waals: van der Waals Forces	84
4.2.4.1 The Dispersion Force	86
4.2.4.2 Repulsive Forces	87
4.2.4.3 van der Waals Force versus Gravity	88
4.3 Crystal Structures	90
4.4 Structures Small Enough to Be Different (and Useful)	92
4.4.1 Particles	93
4.4.1.1 Colloidal Particles	98
4.4.2 Wires	98
4.4.3 Films, Layers, and Coatings	100
4.4.4 Porous Materials	103
4.4.5 Small-Grained Materials	105

4.4.6	Molecules	108
4.4.6.1	Carbon Fullerenes and Nanotubes	109
4.4.6.2	Dendrimers	115
4.4.6.3	Micelles	115
4.5	Summary	118
	Recommendations for Further Reading	119
5.	Nanomechanics	121
5.1	Background: The Universe Mechanism	121
5.1.1	Nanomechanics: Which Motions and Forces Make the Cut?	122
5.2	A High-Speed Review of Motion: Displacement, Velocity, Acceleration, and Force	123
5.3	Nanomechanical Oscillators: A Tale of Beams and Atoms	125
5.3.1	Beams	126
5.3.1.1	Free Oscillation	126
5.3.1.2	Free Oscillation from the Perspective of Energy (and Probability)	129
5.3.1.3	Forced Oscillation	132
5.3.2	Atoms	134
5.3.2.1	The Lennard–Jones Interaction: How an Atomic Bond Is Like a Spring	135
5.3.2.2	The Quantum Mechanics of Oscillating Atoms	139
5.3.2.3	The Schrödinger Equation and the Correspondence Principle	141
5.3.2.4	Phonons	146
5.3.3	Nanomechanical Oscillator Applications	150
5.3.3.1	Nanomechanical Memory Elements	150
5.3.3.2	Nanomechanical Mass Sensors: Detecting Low Concentrations	153
5.4	Feeling Faint Forces	157
5.4.1	Scanning Probe Microscopes	158
5.4.1.1	Pushing Atoms Around with the Scanning Tunneling Microscope	158
5.4.1.2	Skimming across Atoms with the Atomic Force Microscope	159
5.4.1.3	Pulling Atoms Apart with the AFM	164

5.4.1.4	Rubbing and Mashing Atoms with the AFM	168
5.4.2	Mechanical Chemistry: Detecting Molecules with Bending Beams	170
5.5	Summary	172
	Recommendations for Further Reading	173
6.	Nanoelectronics	175
6.1	Background: The Problem (Opportunity)	175
6.2	Electron Energy Bands	175
6.3	Electrons in Solids: Conductors, Insulators, and Semiconductors	179
6.4	Fermi Energy	182
6.5	Density of States for Solids	185
6.5.1	Electron Density in a Conductor	186
6.6	Turn Down the Volume! (How to Make a Solid Act More Like an Atom)	186
6.7	Quantum Confinement	187
6.7.1	Quantum Structures	189
6.7.1.1	Uses for Quantum Structures	191
6.7.2	How Small Is Small Enough for Confinement?	192
6.7.2.1	Conductors: The Metal-to- Insulator Transition	193
6.7.2.2	Semiconductors: Confining Excitons	194
6.7.3	The Band Gap of Nanomaterials	196
6.8	Tunneling	198
6.9	Single-Electron Phenomena	202
6.9.1	Two Rules for Keeping the Quantum in Quantum Dot	205
6.9.1.1	Rule 1: The Coulomb Blockade	206
6.9.1.2	Rule 2: Overcoming Uncertainty	207
6.9.2	Single-Electron Transistor (SET)	208
6.10	Molecular Electronics	211
6.10.1	Molecular Switches and Memory Storage	215
6.11	Summary	216
	Recommendations for Further Reading	216
7.	Nanoscale Heat Transfer	219
7.1	Background: Hot Topic	219
7.2	All Heat Is Nanoscale Heat	219
7.2.1	Boltzmann's Constant	220

7.3	Conduction	221
	7.3.1 Thermal Conductivity of Nanoscale Structures	224
	7.3.1.1 Mean Free Path and Scattering of Heat Carriers	224
	7.3.1.2 Thermoelectrics: Better Energy Conversion with Nanostructures	227
	7.3.1.3 Quantum of Thermal Conduction	229
7.4	Convection	230
7.5	Radiation	232
	7.5.1 Increased Radiation Heat Transfer: Mind the Gap!	232
7.6	Summary	235
	Recommendations for Further Reading	236
8. Nanophotonics		237
8.1	Background: The Lycurgus Cup and the Birth of the Photon	237
8.2	Photonic Properties of Nanomaterials	238
	8.2.1 Photon Absorption	238
	8.2.2 Photon Emission	240
	8.2.3 Photon Scattering	240
	8.2.4 Metals	241
	8.2.4.1 Permittivity and the Free Electron Plasma	243
	8.2.4.2 Extinction Coefficient of Metal Particles	244
	8.2.4.3 Colors and Uses of Gold and Silver Particles	247
	8.2.5 Semiconductors	249
	8.2.5.1 Tuning the Band Gap of Nanoscale Semiconductors	249
	8.2.5.2 Colors and Uses of Quantum Dots	251
	8.2.5.3 Lasers Based on Quantum Confinement	254
8.3	Near-Field Light	256
	8.3.1 Limits of Light: Conventional Optics	257
	8.3.2 Near-Field Optical Microscopes	259
8.4	Optical Tweezers	262
8.5	Photonic Crystals: A Band Gap for Photons	263
8.6	Summary	264
	Recommendations for Further Reading	265

9. Nanoscale Fluid Mechanics	267
9.1 Background: Becoming Fluent in Fluids	267
9.1.1 Treating a Fluid the Way It Should Be Treated: The Concept of a Continuum	267
9.1.1.1 Fluid Motion, Continuum Style: The Navier–Stokes Equations	269
9.1.1.2 Fluid Motion: Molecular Dynamics Style	270
9.2 Fluids at the Nanoscale: Major Concepts	272
9.2.1 Swimming in Molasses: Life at Low Reynolds Numbers	272
9.2.1.1 Reynolds Number	273
9.2.2 Surface Charges and the Electrical Double Layer	275
9.2.2.1 Surface Charges at Interfaces	276
9.2.2.2 Gouy–Chapman–Stern Model and Electrical Double Layer	276
9.2.2.3 Electrokinetic Phenomena	279
9.2.3 Small Particles in Small Flows: Molecular Diffusion	279
9.3 How Fluids Flow at the Nanoscale	282
9.3.1 Electroosmosis	282
9.3.2 Ions and Macromolecules Moving through a Channel	283
9.3.2.1 The Convection–Diffusion–Electromigration Equation: Nanochannel Electrophoresis	286
9.3.2.2 Macromolecules in a Nanofluidic Channel	290
9.4 Applications of Nanofluidics	290
9.4.1 Analysis of Biomolecules: An End to Painful Doctor Visits?	291
9.4.2 EO Pumps: Cooling Off Computer Chips	293
9.4.3 Other Applications	293
9.5 Summary	293
Recommendations for Further Reading	295
10. Nanobiotechnology	297
10.1 Background: Our World in a Cell	297
10.2 Introduction: How Biology Feels at the Nanometer Scale	299

10.2.1	Biological Shapes at the Nanoscale: Carbon and Water Are the Essential Tools	299
10.2.2	Inertia and Gravity Are Insignificant: The Swimming Bacterium	301
10.2.3	Random Thermal Motion	302
10.3	The Machinery of the Cell	305
10.3.1	Sugars Are Used for Energy (but Also Structure)	306
10.3.1.1	Glucose	307
10.3.2	Fatty Acids Are Used for Structure (but Also Energy)	310
10.3.2.1	Phospholipids	312
10.3.3	Nucleotides Are Used to Store Information and Carry Chemical Energy	315
10.3.3.1	Deoxyribonucleic Acid	315
10.3.3.2	Adenosine Triphosphate	320
10.3.4	Amino Acids Are Used to Make Proteins	323
10.3.4.1	ATP Synthase	324
10.4	Applications of Nanobiotechnology	327
10.4.1	Biomimetic Nanostructures	328
10.4.2	Molecular Motors	328
10.5	Summary	329
	Recommendations for Further Reading	330
11.	Nanomedicine	331
11.1	What Is Nanomedicine?	331
11.2	Medical Nanoparticles	332
11.2.1	Nanoshells	332
11.2.2	Lipid-Based Nanoparticles	335
11.2.3	Polymer-Based Nanoparticles	337
11.2.4	Drug Delivery Using Nanoparticles	337
11.3	Nanomedicine and Cancer	338
11.4	Biomimicry in Nanomedicine	340
11.5	Potential Toxicity	344
11.6	Environmental Concerns	345
11.7	Ethical Implications	346
11.8	Commercial Exploration	346
11.9	Summary	347
	Recommendations for Further Reading	347
	Glossary	349

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.

We would also like to make specific acknowledgments.

For their guidance and support, I thank the love of my life, Jill; my vivacious little ladies, Sydney and Quinn; the patient pug, Grace; the nurturing parents, Jim and Sandra; the best of brothers, Judd and Tyler; the big-hearted Hamilton clan; the fresh-thinking Eric Wang; the inimitable Brad Snyder; the late, great Travis Linn; the demanding and kind Jake Highton; the familial Reynolds School of Journalism; and my wise, wise-cracking friends.

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.

Sumita Pennathur is currently an associate professor of mechanical engineering at the University of California, Santa Barbara (BS 2000, MS 2001, Massachusetts Institute of Technology; PhD 2005, Stanford University). She has been actively contributing to the fields of nanofluidics and nanoelectromechanical systems (NEMS), and was awarded both a Presidential Early Career Award for Science and Engineering (PECASE) in 2011, and well as a DARPA Young Faculty Award in 2008.

Jesse Adams (BS 1996, University of Nevada; MS 1997 and PhD 2001, Stanford University) is the vice president and CTO of NevadaNano. He is working to bring multifunctional microsensor technology to the chemical sensing market space.

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

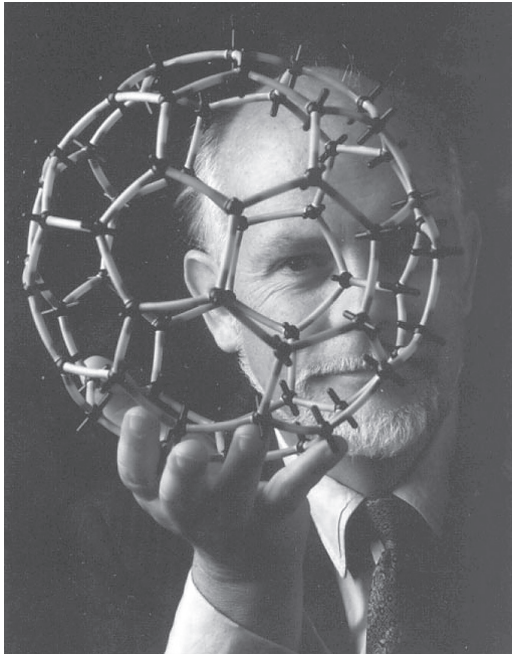


FIGURE 1.1 Richard Smalley. Until 1985, graphite and diamond were believed the only naturally occurring forms of carbon. Then Dr. Smalley, Harold Kroto, James Heath, Sean O'Brien, and Robert Curl discovered another one. It was a soccer ball-type arrangement they called *buckminsterfullerenes* (buckyballs, 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

- [Deja Vu: Aberrations of Cultural Memory \(Electronic Mediations, Volume 12\) here](#)
- [read online 101 Quick Thinking Games and Riddles \(SmartFun Activity Books\) pdf, azw \(kindle\), epub, doc, mobi](#)
- [read online The Complete Photo Guide to Knitting: All You Need to Know to Knit -- The Essential Reference for Novice and Expert Knitters \(Complete Photo Guide Series\)](#)
- [read online Five Types of Ethical Theory \(International Library of Philosophy\)](#)
- [read De la chair À l'extase pdf, azw \(kindle\)](#)
- [download Frommer's EasyGuide to Rome, Florence and Venice 2014](#)

- <http://diy-chirol.com/lib/Deja-Vu--Aberrations-of-Cultural-Memory--Electronic-Mediations--Volume-12-.pdf>
- <http://redbuffalodesign.com/ebooks/World-Made-by-Hand.pdf>
- <http://twilightblogs.com/library/The-Beginner-s-Guide-to-Real-Estate-Investing.pdf>
- <http://creativebeard.ru/freebooks/Five-Types-of-Ethical-Theory--International-Library-of-Philosophy-.pdf>
- <http://hasanetmekci.com/ebooks/The-Meaning-of-Science--An-Introduction-to-the-Philosophy-of-Science.pdf>
- <http://twilightblogs.com/library/Frommer-s-EasyGuide-to-Rome--Florence-and-Venice-2014.pdf>