Steven A. Edwards

The Nanotech Pioneers

Where Are They Taking Us?

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Coverpicture
Eric J. Heller, Nanowire
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Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <http://dnb.ddb.de>.

Printed in the Federal Republic of Germany.
Printed on acid-free paper.

Composition Kühn & Weyh, Satz und Medien, Freiburg
Printing betz-druck GmbH, Darmstadt
Bookbinding Schäffer GmbH, Grünstadt

ISBN-13: 978-3-527-31290-0
ISBN-10: 3-527-31290-0

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Foreword

Nanotech Pioneers provides an insightful look into the nanotechnology revolution, where it is going, and how it will impact us. And it introduces us to the fascinating cast of characters that are bringing it into existence.

Author Steve Edwards has been on the inside track of nanotechnology, as both a scientist and a journalist. Steve has identified the exciting technologies and intriguing players. Some of them are capturing the headlines, and many others you are not likely to hear about, but you will definitely want to know.

The nanotechnology revolution has similarities to the wild forecasts that accompanied the Internet craze, until the bubble burst, but it is very different. Nanotech effects the material stuff the world is made of, including things that make a lot of money, pharmaceuticals, cosmetics, polymers, precious metals, clothing, cars, fuels, steel, diamonds, DNA, cells, bones, blood, brains, computers, semiconductors, biosensors, computer screens, watches, lasers, space travel, pet food, kitty letter, and much, much more. And in each of these situations, nanotechnology has the potential to make money. A lot of money.

Steve Edwards has been a prominent scientific writer and conference organizer who has covered the many advances in material science and nanotechnology, and how they are affecting industry and commerce. I have been a speaker at many conferences where Steve was in attendance, and often a moderator.

I can recall discussions over lunch, or over coffee, at many of these conferences, with Steve and with the other conference attendees, and networking to keep track of the next major advance in technology, the latest scientific papers, the hot companies attracting venture capital, the people moving up, down, sideways or out of the industry. The big companies shopping for technology and applications, or spinning out companies.

Steve was there, listening to this tempo of the business as major advances in science and technology started spilling out of the labs and into businesses. Steve was taking notes and mapping out the trends, the people, the forecasts, and the cool technologies.

At these meetings appeared venture capitalists, economists and government officials, who debated the size of the emerging market, some saying it would be many billions, and some many trillions, of dollars.

In the midst of all these high-minded, breathtaking visions of the future, were entrepreneurs looking for capital, scientists looking for entrepreneurs, reporters looking for stories, consultants looking for consultees, and venture capitalists looking to invest.

Steve has, in this book, captured the spirit and the excitement and the intriguing personalities who have come together to create this new world of business and science. *Nanotech Pioneers* is a great way to see how interesting little ideas are turning into companies, some of which are bound to be the next IBM or Microsoft. And others will fade into obscurity.

Not much happens in burgeoning industries without entrepreneurial energy. What I really like about Steve's storytelling is he mixes accurate science with down-to-earth pragmatics and a real skill for describing the people, and the entrepreneurial network. Too many books and articles on nanotechnology are written by people who don't know the science, and therefore just repeat whatever the entrepreneurs are telling them. Steve, who has a Ph.D. in molecular biology, can separate the wheat from the chaff, and cull out the hype from the real promise. But you do not have to be at all technical to really enjoy this book. Whether or not you are technical, you will be exposed to many of the really cool technologies that are being enabled and impacted by nanotech.

It is interesting how inadvertency plays a role in thrusting people onto the scene of nanotechnology. This happened to me, and Steve has done a great job of capturing how a little thing can change your life and change an industry. I am the CEO of a company, Biophan, and a few years ago a scientist told me that nanotubes could solve some of the problems my company was seeking to solve. The next thing I knew, my company became one of the more talked about and successful nanotech companies. And just a few years later, I was sitting in a conference, listening to a speaker talk about the discovery of tiny little microtubules inside of a deposit of clay in a mine in Utah and, having gotten into a project using nanotechnology, I was attuned to the potential for nanotubes. They are usually made of carbon and created in labs. But here was a fellow describing a naturally occurring nanotube.

Sitting there, in that conference, I could envision dozens of uses and could see how a company could be formed to develop the means to separate the tubes from clay, and apply them to many new applications. I mentioned this to Steve, and explored the situation in depth. Now there is a public company, NaturalNano, pursuing this in earnest. I am an investor, and on the board of NaturalNano. And I am the subject of one of the vignettes in this book. Explaining how this all came about, inadvertently. And that is one of the things I really like about *Nanotech Pioneers*. Steve was there, as this industry has emerged, and watched many of the players reported on in this book run the gauntlet from start-up to success.

But beware, there are some hazards to reading further. The nanotech revolution is contagious, and there is risk you can get roped in! I recommend you hold this book at least six inches from your soul, because nanotechnology is compelling and contagious, once you get what it is about, and what it can mean to the world and to business.

I am fortunate, having been in the nanotechnology field for the past five years, to have met many of the people Steve reports on in *Nanotech Pioneers,* and to be familiar with many of the companies and technologies.

I am so pleased with the job Steve did, knowing – first hand – how successfully he has captured the facts, the promise, the people and personalities, and the excitement, that is driving this revolution.

I agreed to write this foreword, to encourage you to take this book home with you, or on your next business trip, and find out about something going on right around you, in every town and hamlet with a university of a research lab, that is truly going to change the planet and make many things much, much better – and some people much, much richer.

Michael Weiner
Founder and CEO of Biophan, Inc.
Founder of Natural Nano, Inc.

Acknowledgments

First, foremost and always, I would like to thank my wife Sally, who puts up with me and keeps me sane.

Louis Naturman, president and founder of Business Communications Company (www.bccresearch.com) was the one who really put me on to nanotechnology. At first, I told him it was only a buzzword, but I was wrong. It was as editor of BCC's Nano/Bio Convergence News (now, alas, defunct) that I gained a broad understanding of the capabilities of nanotechnology. I have also helped Lou put on nanotechnology conferences for several years now. It has turned out to be an expensive hobby for him, but it has been to the general good, as the speakers at those conferences will acknowledge. I hope that the world will recognize his contribution.

RedZone Profits, a division of Taipan Group, has let me channel some of the information gained in writing this book into income-generating articles on the nanotech industry, for which I heartily thank them.

I would like particularly to acknowledge the many people within the nanotechnology community who have given me information, either in formal interviews or somewhat unknowingly over lunch at a conference. To the latter, I apologize. I never said I wasn't a journalist.

I would certainly like to thank Martin Ottmar and the staff at Wiley VCH for the opportunity to write this book.

I would be remiss if I did not also thank Larry Page and Sergey Brin, the inventors of the Google search engine, an invaluable research tool. I vaguely remember typing my Ph.D. thesis on an IBM Selectric typewriter before there were word processors, but I don't know how I lived before Google came into being.

Steven A. Edwards, Ph.D.
S.A. Edwards and Associates

Chapter 1
The Promise of Nanotechnology

A technological journey is underway – a trip into very small spaces. The journey is led by an eclectic band of engineers and scientists from all disciplines – biology, chemistry, physics and mathematics – who are pooling their talents to create a new field called "nanotechnology". The destination of this journey is not yet entirely clear. Are these nanotech pioneers leading us into a new world of bountiful productivity, or into a dangerous ravaged landscape?

When Lewis and Clark set off from St. Louis, Thomas Jefferson gave them a mandate "...to explore the Missouri river and such principal stream of it, as by its course and communication with the waters of the Pacific Ocean, may offer the most direct and practical water communication across this continent, for the purpose of commerce" [1]. When the Manhattan Project was formed under the greatest of secrecy, the purpose was clear to its participants – to create an atomic bomb that would, by its extraordinary power, put an end to the Second World War. When President John F. Kennedy promised to put Americans on the moon within a decade, there was no doubt as to the destination, although we seem to have forgotten what we were going to do once we got there.

Though funded by billions of dollars from governments around the world and billions more from private industry, the nanotech effort has no overarching mission statement. In this gold rush, the miners have hitched up their wagons and are heading out into uncharted territory. The nanotech journey is open-ended. It is as if, halfway through the Cumberland Gap, Daniel Boone had gathered his followers around him and said, "Well, in a few days we are either going to settle Kentucky, take a tour of Disneyland, or grab a space launch to Jupiter."

One focus of the Nanotech Pioneers is clear: they are out to change the way that we build things now with bulk materials, whittling them down or molding them, to a model that is more like that used by living things, creating objects with defined features that extend to the molecular level. Nanotech seeks to "...rebuild the world one molecule (or even one atom) a time", or so the slogan goes. But is the world really in need of rebuilding?

The more extreme nanotech enthusiasts believe that this new technology will usher in a kind of utopia where material goods will self-assemble from elemental feedstocks in the way that seeds turn into flowers. Some observers, paradoxically, are concerned that nanotech will usher in such an era of abundance that traditional economics based on scarcity will fail, and that the capitalist system and the social organization it has engendered will be in peril.

Nanotech detractors see the technology as extremely dangerous. Some worry about the "gray goo" scenario wherein runaway nanobots run riot and turn the biosphere into dust, destroying human life in the process. Others worry about more conventional environmental contamination – that nanoparticles might have carcinogenic properties similar to asbestos, for instance.

Not since the early days of the nuclear power industry has there been a wider divergence between proponents and opponents of a new technology. Boosters of nuclear power suggested that electric power would become "... to cheap to meter" and that dependence on fossil fuels would fall by the wayside. Detractors warned that reactors would self-destruct in atomic bomb-like explosions, leaving large swaths of radioactive territory that would be uninhabitable for generations. The truth, of course, has been somewhere in between.

In the coming chapters, we will explore the benefits and opportunities of nanotechnology, as well as its potential dangers.

Defining Nanotechnology

What, actually, do we mean by nanotechnology? The term itself was first coined in 1974 by Tokyo Science University professor Norio Taniguchi, who used it to describe the extension of traditional silicon machining down into regions smaller than one micron. By a now more generally accepted definition, today, nanotechnology is the engineering and fabrication of objects with features smaller than 100 nanometers, or one-tenth of a micron. A micron (μm) is one millionth of a meter – too small for the eye to resolve. A nanometer (nm) is 1 thousandth of a micron – that is to say, really, really tiny. One nanometer is about the size of six carbon atoms aligned, or 10 hydrogen atoms – objects too small to see or image except by the use of very powerful electron or atomic force microscopes. So we are talking about a molecular scale.

The thinnest thing, apparently, that most people are generally aware of is a human hair. So texts and articles on nanotechnology will tell you that a nanometer is 60 000 times smaller than a human hair is in diameter. Or sometimes the number is 100 000; nobody seems to agree. I, personally, have very thin, baby-type hair. In a laboratory long ago, in a place far away, for the purpose of impressing my daughter, I took one of each of our hairs and placed them under a microscope. Her hair looked like a cable compared to mine. So I don't use this hackneyed human hair comparison to give people an idea of nanometers. Human hair varies a lot, OK? And mine is almost gone, anyway.

Look at Table 1, which lists the sizes of some fairly well-known biological objects. A white blood cell is about 10 μm or 10 000 nm in diameter. Note that this is actually larger than the interior diameter of the smallest capillaries (8000 nm), so it helps that blood cells are deformable. Bacteria can be as large as a white blood cell, but most are much smaller, on the order of 1 μm in diameter. Viruses are smaller still, with an upper size range of about 100 nm. Nanofabricated objects have architectural features sizes that are equal to or smaller than the diameter of a virus.

Currently mass-produced semiconductor chips can have circuit elements etched down to 90 nm in diameter. However, this is falling rapidly with new nanolithography techniques, which are already pushing the limit down to around 20 nm, or smaller than the diameter of a ribosome, the organelle within our cells that makes proteins.

Carbon nanotubes (see below) can have diameters smaller than 2 nm – hence their desirability as potential components in nanoscale chips. Another staple of nanotechnology, the quantum dot, can be manufactured reliably as small as 2 nm in diameter. These enigmatic objects have a variety of uses in biosensors and in electronics, as will be discussed in following chapters.

Table 1 The sizes of nanoscale objects: Nature versus fabrication.

Object	Diameter
Hydrogen atom	0.1 nm
Buckminsterfullerene (C60)	0.7 nm
Carbon nanotube (single wall)	0.4–1.8 nm
6 carbon atoms aligned	1 nm
DNA	2 nm
Proteins	5–50 nm
CdSe Quantum Dot	2–10 nm
Ribosome	25 nm
Virus	75–100 nm
Semiconductor Chip Features	90 nm or above
Mitochondria	500–1000 nm
Bacteria	1000–10 000 nm
Capillary (diameter)	8000 nm
White blood cell	10 000 nm

Top-Down versus Bottom-Up Manufacturing

Nanoscale manufacturing can occur either from the “top down” or the from the “bottom up.” Top-down manufacturing starts with bulk materials which are then whittled down, until the features that are left are nanoscale. For instance, crystalline drugs may be milled until the individual particle sizes are 100 nm, or smaller. At this size, the particles have a much larger surface area in relation to volume than would more conventional microscale particles. This allows them to dissolve much faster – which is critical for certain drugs that are not very soluble in water.

Bottom-up manufacturing involves creating objects or materials from individual atoms or molecules and then joining them together in a specific fashion.

Think about how a table is built. A plank of wood is connected to three or four posts, through the use of screws and wood-glue. The posts may also be made of wood. Simple enough. This is classical bulk material manufacturing. But how is the wood made?

Wood is created by joining molecule to molecule according to instructions decoded from the DNA in the cells of trees. Tree-trunks may extend hundreds of feet into the air, bringing water from the roots to support branches and leaves. Whole ecosystems that live in the upper reaches of the rainforests are dependent upon this remarkable material. And yet, wood is synthesized at the nanoscale by the individual cells of the tree.

What is the chemical composition of wood? Wood is largely made of cellulose, which is in turn composed of repeating units of glucose, a simple sugar (a single unit is shown in square brackets in Fig. 1). A related material, potato starch, is also composed of repeating units of glucose (Fig. 2). So why can't we build houses out of potatoes? Unlike cellulose, potato starch is not rigid at all. The differences between cellulose and starch reside primarily in the molecular link that connects one glucose units one to another. These links translate into wholly different properties.

This is the promise of nanotechnology – to find extraordinary properties in the arrangement of simple materials.

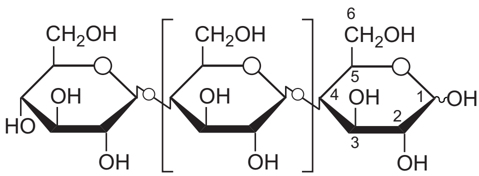

Figure 1 The chemical composition of cellulose. Brackets indicate the boundary of a glucose subunit. The carbon numbering system is indicated in the last subunit to the right.

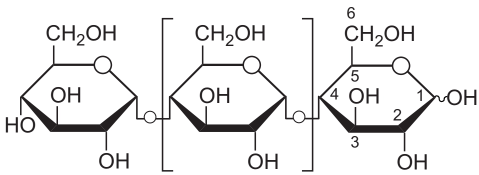

Figure 2 The chemical composition of starch. Note that the only difference between the two structures lies in the placement of the bond between glucose subunits.

Cellulose is composed entirely of carbon, hydrogen, and oxygen, as shown above. Burn a tree trunk and the cellulose will be oxidized to carbon dioxide and water. However, because a fire is rarely completely efficient, the ashes remaining will contain a lot of elemental carbon remaining in the form of soot.

What is in Soot? The Different Forms of Carbon

A component of soot is colloidal carbon, which is also manufactured under more controlled conditions as carbon black. This is a nanoparticle that has been used for centuries as a pigment in inks, paints, and finishes; today, it is also used as a reinforcing agent in rubber, notably in tires. Carbon black is actually small enough that it will enter the skin. Workers at tire factories may sweat out carbon black onto their clothes and sheets for a week or two after they have ceased employment.

Elemental carbon is also used in the form of graphite as a lubricant (Fig. 3), or to make extremely strong carbon fiber material used in bicycles and tennis rackets.

A rare component of soot is a cylindrical form of carbon called a nanotube. Carbon nanotubes can be thought of as a single layer of graphite (called a graphene sheet) rolled into a cylindrical tube. Variants of the structure exist, depending on

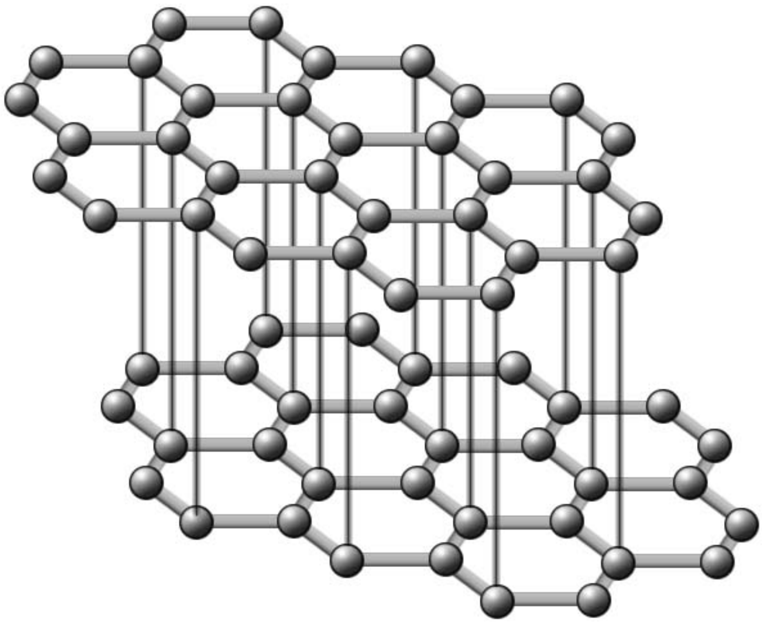

Figure 3 Molecular model of graphite. Each of the atoms is a carbon molecule bound to three other carbon molecules in the same plane. The planar surfaces do not have covalent links and are therefore free to move relative to one another, which gives graphite its lubricant properties. Image reproduced courtesy of Samantha J. Shanley, University of Bristol.

how the ends of the sheet connect and the diameter of the cylinder (Fig. 4). These tubes may or may not have a curved cap on either end. Carbon nanotubes are many times stronger than steel, and conduct electricity better than copper – as will be discussed in a later chapter. Carbon nanotubes have become iconic devices for the field of nanotechnology. Small companies are now in the process of developing nanotubes into transistors and memory devices for computers. It is expected that ton quantities of carbon nanotubes will be produced annually within a few years.

Under extreme pressure, elemental carbon will also spontaneously form into a very different crystalline form called a diamond (Fig. 5). Diamond is the densest form of carbon, packing the most atoms into the smallest area. (Next time you see a multi-karat chunk of diamond on somebody's ring, don't get jealous; just remind yourself that it's basically a hunk of very compressed charcoal).

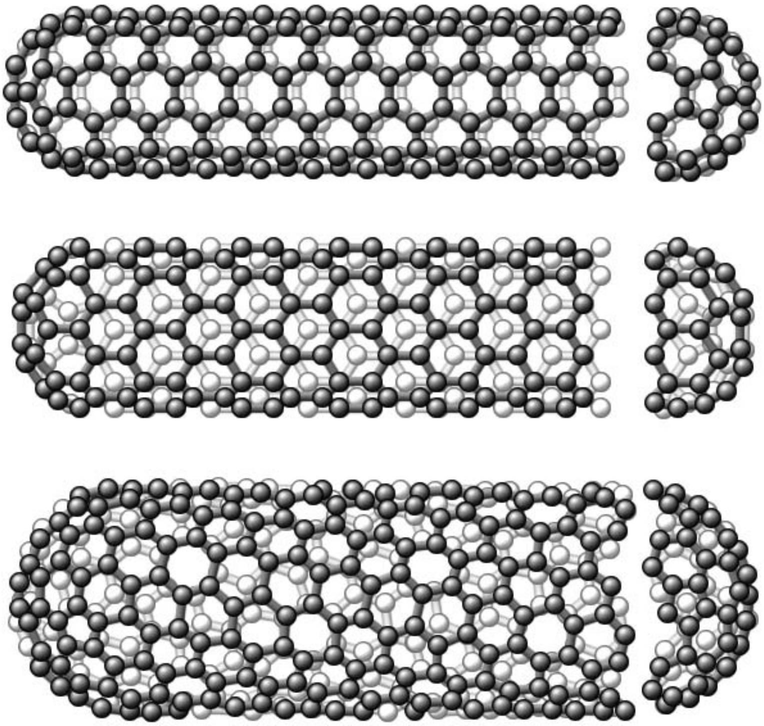

Figure 4 Carbon nanotube structures. Each carbon is bound to each other in a cylindrical arrangement. These may be thought of as graphite planes that have been cut and rolled up. Slightly different arrangements occur, depending upon how the sheets are cut and the diameter of the tube. Tubes may or may not have a cap at either end. Images reproduced courtesy of Samantha J. Shanley, University of Bristol.

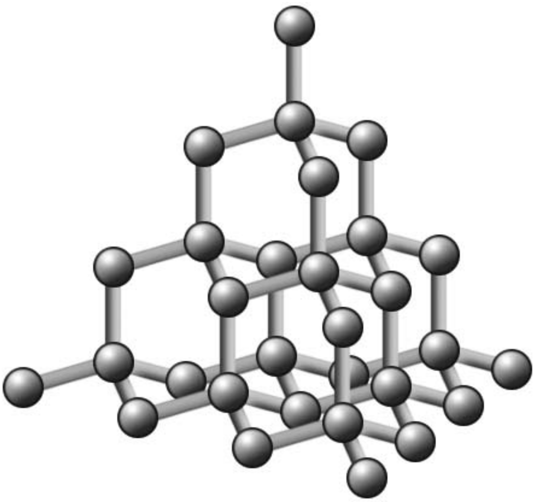

Figure 5 Molecular model of diamond. Each carbon atom is bound to three others in a three-dimensional crystal. Image reproduced courtesy of Samantha J. Shanley, University of Bristol.

An even more striking version of carbon is a molecule called buckminsterfullerene, because it's structure resembles the geodesic domes built by the famous architect and visionary Buckminster Fuller. Formally, this structure is called a truncated icosahedron, and consists of alternating hexagons and pentagons. Look at it closely and you will notice it looks more or less exactly like a soccer ball (or football to all but Americans – we have our own eccentric version of a football) with the same arrangement of pentagons and hexagons (Fig. 6).

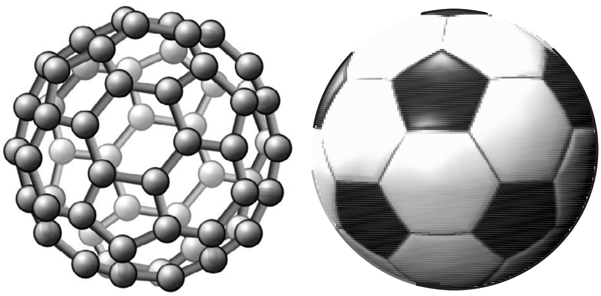

Figure 6 Chemical structure of Buckminsterfullerene-C60. Each carbon is bound to three other carbons in a pseudo-spherical arrangement consisting of alternating pentagonal and hexagonal rings, in the manner of a soccer ball. Hence its nickname, buckyball. C60 image reproduced courtesy of Samantha J. Shanley, University of Bristol.

Common to diamonds, graphite, carbon black and carbon nanotubes is the chemical formula – C_n – where n is the number of carbon atoms. All of the wildly different attributes of the various forms of carbon come about merely through the altered arrangement of those carbon atoms into molecules. Though carbon linked only to itself comes in a variety of forms, it hardly stops there: in combination with other elements, carbon forms about sixteen million different compounds. All life, as far as we know, is based on carbon chemistry.

If we can get this much utility out of carbon, how much more can we do with control over the placement of over all of the available elements?

An Alternative Nature

Biology, for all its genius, paints with a limited pallet – mainly carbon, hydrogen, nitrogen, oxygen and phosphorus, with some trace metals and salts thrown in for variety. These, in turn, are elaborated into only a few basic molecular types – proteins, nucleic acid, lipids, and carbohydrates. In contrast, chemists have the whole periodic table with which to work their magic. Until recently, their methods were relatively primitive and only small molecules could be efficiently manufactured. Now, nanotechnology seeks to unite chemists with physicist, engineers, and biologists to create molecular structures of unprecedented complexity and size. These structures can be used to create new materials and even nanoscale machines and artificial organisms. We are on the verge of creating what might be described as an alternate Nature.

All living things on this planet, from the tiniest virus to the tallest tree to the sperm whale in the ocean, share the same genetic code and substantially the same manufacturing scheme for putting together their various components. Out of the science of molecular biology came the recognition that there is substantial unity in the biochemical make-up of all creatures on the planet.

Now suppose that we could consciously control manufacture at the molecular level in the way that living things do. Inorganic components could be married with biomolecules. Building materials could have intrinsic self-repair capabilities. Skyscrapers could, in theory, be built such that the whole structure was covalently linked into one super molecule. Would this be a better way to build things?

Money Makes the World Go 'Round

The problem with some more enthusiastic blue-sky scenarios – the fly in the blue-sky – as always, is economics. In Neil Stephenson's sci-fi epic *The Diamond Age* [2], one of the first fiction works to focus on nanotechnology, buildings were grown from seed and raw materials with the help of molecular assemblers. Imagine, for instance, that you could grow a barn that way. Or you could hire a few Amish farmers and they will nail up a lovely barn for you in a weekend. Which really makes the most sense, from an economic standpoint? It would take a lot of barns to justify the development costs of the nanotech version.

Money, as the immoderate emcee in Bob Fosse's Cabaret reminded us, is what makes the world go 'round. Without its commercial appeal, nanotechnology would not go far. Nanopioneering products so far been modest in terms of products that have been produced and profits they have generated. Small nanoparticles are used to make sun-blocking cosmetics. Nanoparticles are also used as a slurry to polish silicon used in making semiconductors. Carbon nanotubes have been used as a reinforcing material in tennis rackets and in polyurethane. NanoTex stain-resistant fabrics are used to make clothing. Mercedes-Benz includes in its paint jobs nanometer-sized ceramic particles that makes the surface more scratch-resistant and helps keep it glossy. Similar particles are used in floor tiles. InMat had developed a thin coating for the inside of tennis balls that retards the loss of air pressure, extending their useful lifetime. There are potential applications of this process for everything inflatable, from car tires to helium balloons.

And what about self-cleaning windows? Talk about a boon to humanity! This invention relies on a coating, only 40 nm thick, which contains a photocatalyst that uses the sun's UV energy to break down organic debris that collects on the windows. A second feature of the coating is that it is chemically hydrophilic (water-loving). Water does not bead up on the glass, but sheets off evenly.

A scientist at the University of Queensland, Michael Harvey, has invented a nanoscale coating called Xerocoat that is actually a thin film of glass full of tiny bubbles. Xerocoat prevents fogging on such things as spectacles, automobile windows and bathroom mirrors. "We are taking nanotech out of the lab and putting it in the bathroom," says Harvey.

Nanotechnology has already established a foothold within your computer. The read-heads of newer hard drives are built by the nanoscale deposition of thin films of "giant magnetoresistant" material. This material has the property of changing its resistance to the flow of electricity when it encounters a magnetic field. The read-head glides over the hard-drive at speeds up to 80 miles an hour suspended on a cushion of air only 10 nm above the surface of the drive. The magnetically encoded data on the disk are translated into electrical current as the read-head flies along.

In terms of dollar volume, the most important nanotech products right now are probably nanoparticle catalysts used in the distillation of petroleum and its byproducts.

The real harvest of nanotechnology is yet to come. But technology does not develop in a vacuum. Ideas do not jump from the head of a scientist or engineer into reality. The translation of ideas to prototype to product requires great inputs of both toil and capital. And all of that ingenuity and investment may be wasted if the society or the market is not ready for the final product.

Who Knows About Nano?

"Everybody knows that nanotech is important," says Bob Gregg, executive vice president of FEI Corp., which makes electron microscopes. "Just mention the word, and you can get a meeting with anybody [in the federal government] in Washington D.C. Of course nobody knows what it means ..."

Despite a fair amount of media coverage, the promise of nanotechnology is not much appreciated by the general public. This was brought home to me last year, when I gave a presentation at a convention called 'Imaging and Imagining Nanoscience and Engineering', sponsored by the University of South Carolina in the city of Columbia. The night before my talk, as usual, I ran through my slides and gave a solitary performance for the benefit of my reflection in the window of my hotel room. This kind of concentration at night tends to get me too wired to sleep, so I went down to the bar. At that time, perhaps 25 people were assembled there in various states of intoxication. I quickly met up with a man who was staying at the hotel as a mentor for a convention of teen-age journalists. Despite being a journalist and therefore open to a wide variety of general information, this man claimed to have never heard the word "nanotechnology." Emboldened by a couple of beers, we proceeded to poll those assembled in the bar to determine if any of them understood the term. There was exactly one other patron there, other than myself, who admitted to knowledge of nanotechnology. An aerospace engineer, he opined that the university and state government were interested in nano only because they thought it would somehow provide jobs for South Carolina. This particular engineer was African-American; ironically, his female companion was at first very adamant that he not talk to us. Because she was a northern black recently moved to the South, she had the mistaken impression that my journalist compadre and I were engaged in some Southern whiteboy crusade to prove that black people were ignorant. I am quite sure that most people in the United States – white, black, Latino or indifferent – either have never heard of nanotechnology or have a vast misunderstanding about what it is about. I doubt that the rest of the world is any different.

Senator Ron Wyden (D.-Oregon), who is the co-author of the Twenty-First Century Nanotechnology R&D. Act, tells the story of one of his constituents, an elderly lady, who accosted him a local supermarket. "Senator Wyden, I don't know much about this 'nano-nology'," she says, "... but I'm glad you're doing it." Hopefully, this book will increase public knowledge about nanotech, the people behind it, and why they're doing what they're doing.

Nanotechnology requires not only scientists and engineers, but also entrepreneurs with vision, not to mention patent lawyers and marketing agents. Right now, nanotechnology is the sphere of a small number of entrepreneurial companies and a few large giants, like IBM, that have an eye for the future. An economic depression, a World War or an overwhelming natural disaster, like global warming, have the potential to derail the technological future in the making. At least for a while.