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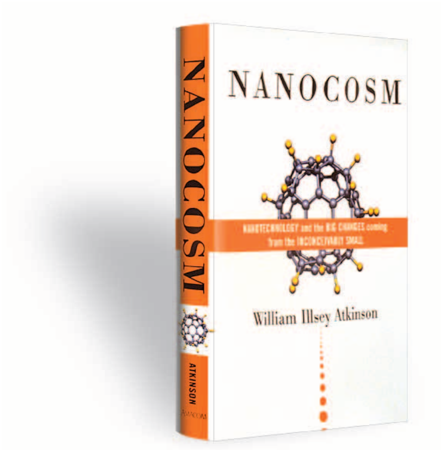

By William Illsey Atkinson

Nanotechnology and the Big Changes Coming from the Inconceivably Small

NANOCOSM

THE SUMMARY IN BRIEF

Since the beginning of the industrial age, many machines have grown steadily smaller even as they have grown more powerful and complex. Now nanotechnology, based on a new science of the infinitesimally small, takes technology beyond most popular definitions of reality, to a realm of molecular machines, cell-sized computers and other astounding possibilities. In Nanocosm, *technology consultant and writer William Illsey Atkinson reveals a spectacular view of the immediate future of nanotechnology and its applications in medicine, computing and engineering and countless other arenas that affect our world, redefining how we work, play and live.*

As with any phenomenon, nanotechnology has both its naysayers and its zealots, by turns clouding scientific truth with dismissals, prophecies and pipe dreams. But nanotech is real. President Bush announced recently a $500 million National Nanotechnology Initiative and BusinessWeek *has named nanotechnology one of the ten technologies that will change our lives.*

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What You'll Learn In This Summary

✓ **What nanotechnology is and why it's so important.**

✓ **How to understand the concepts behind the hype** so that you can make informed decisions about whether to support a particular nanotech initiative as an investor or venture capitalist.

✓ **How countries around the world are investing in nanotechnology**, helping to provide a first boost to research that can result in the commercialization of promising nanotechnology.

✓ **What changes are possible in the next few years**, including the possibility that drugs can assemble themselves and cause minimal side effects and how engineers will build mega-structures with strength and stability.

✓ **How to tell the nanotech charlatans from the real scientists.**

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NANOCOSM

by William Illsey Atkinson

— THE *COMPLETE* SUMMARY

Lower, Slower, Smaller

The most amazing thing about nature is her inexhaustible variety. Scientists, technologists and theologians speak about nature or the world as if it were a unit. But there are limitless worlds and infinite natures.

Merely varying your dimensional scale creates new worlds. Karl Marx is justly discredited as a social philosopher, but one of his points was incontrovertible: Quantitative differences create qualitative difference. In other words, scale matters — change the numbers and you change the thing. For example, our usual human view looking out from the surface of the planet differs from what we see from the orbit of the moon. All cosmonauts and astronauts agree the most conspicuous thing about viewing earth from space is the invisibility of national borders.

Seeing the world from the outer edges of the Milky Way offers yet another view. Turn inward rather than outward and peer with ever-higher magnification into the world of the small and you get another perspective. Each subworld embodies an alternate reality. Scale of *millimeters* brings us to the world of insects. Drop down a notch and you enter the world of the *micron*, a unit whose length is one thousandth of a millimeter. This subworld is literally the microcosm. It is the world of the cell — autonomous units like amoebas as well as specialized populations of cells that make up skin, bones and brain.

Below the microcosm comes creation on the scale of the *nanometer*, one millionth of a millimeter. This is the nanocosm. It is a finely detailed, completely structured cosmos, self-assembled atom by atom. The subworld is a place onto itself. The rules are neither those of galaxies nor what we see within the middle kingdom we inhabit.

We have now mapped out enough of the nanocosm to make educated guesses about what it can support. Some very big changes in business and leisure are about to come to us by way of the very small. Unfortunately, there is also a lot of hyped up public expectation. One reason is that some scientists have been boosters of a technology even before it was close to existing.

Twenty years ago while pursuing his doctorate at MIT, K. Eric Drexler wrote the first journal paper on advanced nanotechnology, envisioning what it might be. Dr. Drexler boldly foresaw a world of molecular manufacturing, where macroscale objects were assembled atom by atom by nanoassemblers the size of molecules. Ten years ago he expanded this initial vision into a book, *Nanosystems: Molecular Machinery, Manufacturing, and Computation.*

The book is radical only in its subject matter because it takes a classical approach to the actual engineering needed. The book admits no difference between building a suspension bridge and creating a bloodstream-cruising submarine. The nanocosm is only another arena where engineers can apply known techniques. The book is a highly detailed piece of speculation.

Despite these imaginings by a fringe of boosters, there are strong signs that a workable nanotechnology is at last being born. Advances are occurring daily. While most are in basic nanoscience, business indicators such as number of start-ups, IPOs and venture capital pools indicate that a viable commercial enterprise is emerging.

Nanotechnology

In a sense, all technology is nanotechnology. That's because everything we use relies in part on the properties of matter at the nanoscale. Take tires, for example. What makes them flexible and strong is the addition of nano-sized particles of soot to rubber.

What sets apart today's nanotech from traditional activities such as tire making is intent. When we devise and manufacture today's nanocomposites, we know what we are doing — in fact, we can directly see it happen. Nanotech will soon let us bypass the substances that nature provides and start with a wish list of properties that a new

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Lower, Slower, Smaller

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material must have. In five to seven years you'll be able to call a nanomaterials firm and tell them what you need.

The nanocosm will transform us. It will not content itself with revolutionizing grand things: economy and culture and democracy. It will alter, from the inside out, the small details that affect us — how we stay healthy, spend leisure time and raise our children. ■

Nanoworld

A decade today brings with it a vast transformation. And the speed at which transformation happens is about to take another leap. Sometimes it seems almost impossible to imagine what things were like technologically ten years ago, much less a century ago.

Political revolutions happen suddenly. On Monday a despot sits entrenched, on Tuesday there's a local food riot, on Wednesday the disturbance spreads and the despot is dead or in exile by the weekend. The causes may be ancient but the effects take place in a flash.

So far, at least, revolutions in science and technology have taken longer to occur. The Industrial Revolution took a century and a half, the Agricultural Revolution, two or three millennia. The extent of the change and its economic and cultural impact was hardly apparent at the time.

This is true even today, when the pace of technological change has increased. Telephones, cars, cotton clothes and sanitary sewers — the triumph of these things was steady but slow. Even computers didn't achieve supremacy overnight. Only in retrospect was a technological revolution apparent. Yet revolution there was. In a mere decade, you will be shocked when you look back at 2003 — this year will feel like the Middle Ages.

Nanoscience

Say you're a galactic intelligence from beyond earth: a physical scientist. You come across earth in one of your periodic expeditions and settle in to study it. The patterns are immediately apparent. Earth is a planet, revolving at a nearly constant distance from a yellow dwarf star. It is almost perfectly round and rotates slowly about an interior axis. Its temperature varies so that there are seasons everywhere outside a narrow band around the equator.

You zoom in and see hurricanes, mountain ranges, and archipelagos. Further in yet you see artificial structures, ships, trains and aircraft which are indications of a genuine civilization. Finally, you see fixed organic structures that take in carbon dioxide and emit oxygen as well as organic structures that do just the opposite, creating an endless loop. Keep going, and soon things get smaller — yet another frontier: nanoscience.

What is nanoscience? A leading expert is Dr. Doug Perovic, chair of Materials Science and Engineering at the University of Toronto. He reminds us that all science studies matter and energy, whether it's physics, chemistry or biology. As each field advances in its discoveries, each is collapsing into a new structure, a nanostructure. Each discipline is looking deeper and deeper, and discovering that at the nanoscale, matter looks and acts the same.

One aspect of this exploration of the miniature world is bio-nano — the study of living systems at the nanoscale. Here, scientists are looking at what nature already does. More importantly, they are coming up with ideas that can be taken from nature and used — what Dr. Perovic calls biomimicry. For example, microscopic rotational motors already exist in nature. They power the whip-like flagella of E. Coli. There's no reason we can't swipe these designs, tweak them and use them in our own inventions. ■

Nanotechnology Trends in World Development

For something that's so new to serious investigation, the nanocosm has shown itself amenable to commercialization at a record-setting pace. Today the discoveries reported in a typical journal paper may be well on the way to being commercialized before the article even appears in

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The Swiss Nano Miracle

Switzerland, a tiny country, lives by its wits and has for centuries. It is a feisty, indomitable, brainy and elitist nation. Consider its watch industry. For years Swiss watches were second to none as watchmakers created elegant and accurate timepieces. Then along came microchips and accurate gears and wheels were no longer necessary. Instead of giving up, the Swiss reinvented their watch industry. First they developed the Swatch — a line of stylish low-cost watches designed and marketed to young people. Second, they created ultra-high-end timepieces that became wearable jewelry that conspicuously display success.

But watches are only the start. The Swiss have fleshed out that industry with some of Europe's greatest concentrations of wealth based on high-tech. This includes biotechnology, chemicals, banking and pharmaceuticals.

The Swiss locate hot new technologies, sweat blood to become proficient in them and then ramp them up to be massive moneymakers. The whole culture is a perfect Petri dish for nurturing new ideas like nanotechnology.

Nanotechnology Trends in World Development

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print. But nanotech had to overcome some steep financial hurdles to achieve its present success. That's because the dot-com boom and bust affected investors' willingness to support and finance new ventures.

To understand why, you need only look at events of the late first few years of the twenty-first century. By mid 2000, the promise of advanced technology had convinced most mainstream banks and venture capitalists that business plans didn't need bricks, mortar and land to be worth funding. Intellectual property, investors realized, could be collateral as sound as real estate. Then the investment pendulum swung the other way. As if to undo its years of under funding and neglect of high tech, capital went on a spending spree. Dot-com mania became a land bubble for the chalk stripe set, who often ignored due diligence in their lust to profit from high tech. They learned that wild wishes aren't intellectual property, that launching an IPO is not a business plan and that stock itself is not a product.

The result was a tightening of the purse strings. Only the soundest nano-ideas are now being funded, resulting in the commercialization of promising nanotechnology.

Fledgling technologies begin their capitalization with public money. Funds are assigned indirectly through university research teams or directly through state and federal labs. For example, in 2001 the US government budgeted $422 million for nanoscience research and development. Funding for the National Nanotechnology Initiative is expected soon to increase even more.

France, Germany and the United Kingdom have also established national research programs in nanoscience. Korea, Taiwan and China have said they are starting initiatives and even Canada, with a population and economy the size of California, has a brand-new National Nanotechnology Institute.

Of the initiatives just cited, Canada's is the one most likely to impact the United States. That's because under the North American Free Trade Agreement, Canada and the United States share a seamlessly integrated high-tech economy. Every Blackberry pager comes from Canada. So does half the transmission hardware in many North American telephone companies.

However, the USA's biggest competitor in commercial nanotech will be Japan. Japan has identified nanotechnology as *the* key discipline for its future economy. The Japanese want to dominate every key sector in nanotech within 15 years. Already they have made major advances in such nano-areas as energy-miser spintronic computers, frictionless pumps, and self-bracing structures. ■

A Venture Capitalist's Take On the Future of Nanotechnology

Dr. William Warren is an Oklahoman well versed in the emerging technology we call nanoscience. A Penn State engineering graduate, he is president of Sciperio, Inc., a venture capital firm with interests in ceramics and molecular electronics, water purification and advanced manufacturing. He will tell you that nanotech was first pushed by former Vice President Al Gore because he wanted to throw a bone at the physical sciences. Gore sold Clinton on nanotech, but when he didn't win the 2000 presidential election, anyone who was behind the nanotech program cut and ran. What they hadn't figured out, explains Dr. Warren, was that by then, too much time had gone by for anyone to shut the program down. Nanotech had too much momentum — people had already started research and spending money. Constituents told their representatives and senators they wanted the National Nanotechnology program continued and President Bush had no choice but to do so. He did even better — he expanded it.

Dr. Warren is taking advantage of the boom in development. He has configured his VC firm in an unorthodox way. The firm acts as an administrative core, vetting new technologies and locating funding for them. The company does not itself undertake any commercial development: it spins off daughter companies for that. Those companies in turn seek more VC and angel funding but also go public.

Nanofornia

Small Times is a trade magazine that covers both nanotechnology and MEMS (microelectronic mechanical and electrical systems). The magazine recently identified six U.S. hot sports in nanotech. The hot spots are:

- **Silicon Valley**
- **Southern California around Los Angeles**
- **Boston**
- **New York City**
- **Dallas/Houston**
- **Chicago**

Silicon Valley, concluded the magazine, had just the right combination of youth, money, brains and the gold rush spirit. This is a young place, but a fabled one. It starts in southeastern San Francisco and stretches down, mostly inland from the Pacific Ocean. As late as 1960, America thought of this area as Steinbeck country. But however much American loves its writers, it loves its

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Nanofornia

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money more. As a nation, the United States reserves its highest accolades for business people, measuring success less as lives illuminated than as dollars accumulated. Hence the towering profile and long shadow of the Silicon Valley myth.

It was here that the integrated circuit first took shape and the personal computer was conceived and delivered. From Oracle and Sun Microsystems to IBM's Almaden Research Center to Xerox's Palo Alto Research Center and the academic know-how at Stanford University, Silicon Valley was the place the future was born. And judging by the fervor with which nanoscience is being adopted, it still is.

Silicon Valley still has "it." As well as world-leading research nodes, "it" included enormous pools of venture capital; experienced facilitators, analysts, and consultants; and thousands of firms with expertise applicable to nanotech. Even more important is the culture so prevalent in Silicon Valley. Failure is valued as a learning experience. *Small Times* writer Candance Stuart observed that "if they tumble, they regroup and try again."

The Future of Nanotech

There is a lot of promise in nanotechnology, but especially in the U.S., progress will be incremental and market-driven at first. It will be a process similar to that of solar energy. Years of research and billions of dollars were spent on fancy ways of converting sunlight to energy, but the first really practical application was the solar blanket. That simple innovation takes the sun's energy and heats the water in swimming pools, reducing the need for gas or electric heaters.

Few people outside the scientific community have a ready grasp of nanotech. In particular, venture capitalists are struggling to understand the scientific breakthroughs they are being asked to fund. And many are very nervous about funding any ventures, having been burned badly in the Internet boom.

Fortunately, there are other sources of funding stepping in to ensure there is continued progress. Federal and state programs, even municipal ones, are now the best place to look for seed money for nanotech ventures. These new sources of financing won't be as free and easy with money as the venture capitalists of the last decade, but some funding is better than none.

Nanotech is still an infant technology but big advances are coming soon. Experts predict that:

- Through 2004 new discoveries in basic nanoscience should emerge.
- From 2004-2008, expect the development of emerging new nanotechnologies.
- From 2008 onward, look for a surge in the mass production of nanomaterials, biomimetic software modeling and nanosurgery.

Quantum Weirdness

Dr. Drexler, who coined the term nanotechnology twenty years ago, believes firmly that his version of using the nanocosm will revolutionize the world. Nanoscale machines will create things from the bottom-up, atom by atom: new drugs and synthetic materials and even copies of themselves. This, Dr. Drexler declares, will lead to RIE, a Revolution in Everything. Transportation will improve; nanomachines will destroy viruses and cancer cells, remove accumulated wastes from the brain and bring the body back to a youthful health.

Everything will be accomplished by little machines. The Drexlerian nanobot, he asserts, will be tiny. In the process of writing and speaking about his view of nanotechnology, he has amassed a loyal following. His doctrine has taken on almost a religious air among the engineers who have become known in the scientific community as nanoboosters. ■

Nanotech and Data Compression

As you are no doubt aware, information gobbles up lots of computer memory. Visual images take up even more, but everyone wants fast Internet access with pictures, motion and sound. A picture may be worth a thousand words, but it takes up a hundred thousand times the disk space of mere text.

Engineers have found ways to crunch visual information so that is places less load on IT hardware. If you're sending video, you can transmit each successive still picture by specifying only what's changed since the still that came just before. This is called a compression algorithm. But nanotech promises a better way, modeled on the way the human body works. Our eye-brain system has something called an orientation reflex. This briefly speeds perception when we shift our gaze, especially when we are alarmed or startled. If you've ever glanced at the office clock and thought its second hand had frozen, that's the orientation reflex. In emergencies, it appears to slow down time.

Duplicating such an elegant efficiency in an artificial system, thereby letting it adapt effortlessly to changing circumstances, would mark a massive advance in visual IT. Once again, it's clear that the most important thing we have to do in exploring the nanocosm is to shut up and learn.

For Additional Information on on Dr. Drexler and his theories, go to: http://my.summary.com

Wet Nanotech

Total direct world funding in nano-activity — in technology and science, both public and private — will likely exceed $5 billion by the end of 2003. Indirect funding will exceed this figure many fold. The main reason for this rapid growth lies in a single subsector of nanotech. The life sciences, including genomics and biopharmaceuticals, are both the biggest area of nanotechnology R &D and the largest single source of nanotech funding. The biosciences are pushing ahead into nanotech faster than any other academic or commercial sector, even information technology. Biosci is central to the clear majority of nanotech start-ups.

One reason advances are coming fastest in bioscience is that researchers in that field have been working at the molecular level for a hundred and fifty years. Because theirs is a more mature science already reaping the benefits of years of research, they have cash-rich customers willing to fund further exploration into the miniature world of nanotech. Bioscience can combine the advantage of available cash, extensive knowledge and skill sets and transfer them to nanotechnology.

Interestingly, many nanotech boosters have an almost contemptuous disparagement of existing technologies. These boosters say that classical approaches to discovering and doing things, from bridge building to chemical engineering, rely on techniques that at the atomic or molecular level are so crude they are laughable. Far better, claim the boosters, to treat atoms with the respect they deserve — handle them one by one. Boosters see a world in which they will design and build structures de novo on the nanoscale.

Nano boosters have a term for bioscience: It is, they say, just "wet nanotech." In their view, it's time to take nanotechnology out of the kiddie pool, towel it dry and send it off to do adult things. Atoms, they say, should be handled one at a time, with a watchmaker's meticulous care. Chemical synthesis will eventually become a subset of mechanical engineering, claim these nanobooster engineers.

The problem is that the nano boosters are making two errors. First, they fail to see that standard engineering principles cannot simply be taken from the macro-scale and applied immediately to the nanoscale. The nanocosm is totally, bizarrely different. Change in scale changes the thing. Second, "wet nanotech" (i.e. nano-bio, bio-nano or bioscience) has emerged from being the boosters' whipping boy to become the dominant force not only in illuminating the nanocosm but also in exploiting it.

The Power of Wet

It turns out that "wet nanotech" has a lot going for it. The biosciences constitute humanity's most sophisticated set of techniques for manipulating matter. That they do so en masse, with up to twenty-eight orders of magnitude worth of molecules at a time, does not matter. Wet nanotech can still reach high levels of reaction predictability and product accuracy.

There is another compelling reason that the future of nanotech lies with the classically trained scientists. The sub-micron world is not a quiet one, waiting to be manipulated by engineers who foresee tiny devices quietly assembling atoms into exactly what they want. At the molecular level, there is a whole lot of vibration going on. Perhaps the best way to visualize the problem is to imagine a tiny submarine traveling through the blood stream — assuming such a nanobot could ever be built. The same forces that perpetually agitate living material and the nonliving molecules that lie within it, would batter an artificial nanomanipulator into junk. To a synthetic submarine cruising the bloodstream random molecular collisions would seem like an avalanche of ten-ton buildings arriving head on at a hundred miles an hour. Our imaginary nanocraft would be smashed in seconds.

Contrast this with the classical biochemists' approach. They use molecules to manipulate matter — molecules that have been designed by nature to withstand the violent storms experienced in the human bloodstream and other organisms. These are the true molecular assemblers, and they are more rugged than cast iron.

Push and Pull

Bioscience is currently spinning off a wide variety of technologies, ranging from medical therapeutics and diagnostics to entirely new molecular approaches to molecular computing. These technologies equal or exceed the functions that nano boosters imagine for their nonexistent nanoassemblers.

Technology push is the process by which those who

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Nanotech at Work

A promising biochemical process is creating excitement in the nano-world. The technique is called site-specific mutagenesis, and won biochemist Michael Smith the 1993 Nobel Prize in Chemistry. It lets biologists zoom in to a precisely predetermined location on a huge DNA helix, hold it immobile, and alter it by as little as a single atom. This is microsurgery on the molecular scale. If you inspect things from an IT viewpoint — as many bioscientists are doing, using another brand new discipline called bioinformatics — you realize that Smith's invention is a molecular editing function. Search, find, delete, insert, modify. This is word processing for ACGT, the four letter alphabet of life.

Wet Nanotech

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originate ideas (for example, nonprofit R&D institutes, universities and government labs) try to get their findings into the commercial world and earning money.

Technology push doesn't always work. For one thing, basic researchers often overestimate the impact of their raw results and underestimate the sweat it will take to commercialize them. And many scientists don't feel comfortable making the rounds looking for the capital needed to make their discoveries useful.

Fortunately for nanotech, another force is also at work — *market pull.* This is the force exerted by the private sector to locate promising knowledge outside its own labs, assess it, buy or license it, adapt it and package it to sell. The past masters of market pull are the international biopharmaceutical companies. The big drug firms have full-time staff whose only job is to scan the scientific literature for the first sign of a potential product. Their search is not limited to formal journals. It extends to reading discussion papers and even overhearing gossip at scientific conventions.

The biopharm scouts tour labs and persuade scientists to sign away present and future intellectual property for stock options and residual payments that will materialize if and when their research leads to a marketable process or product. The scouts' ace in the hole is to offer what every scientist lusts for — further research funding. For all these reasons, today's bio-industry is already in the lab, influencing what is studied, how and when. Multinationals perch like ravens on laboratory windowsills, blank contracts in their claws. Despite the questionable ethics, it's indisputable that bridges open overnight between new facts and new financing. The intensity of market pull from the biopharms constantly advances wet nanotech.

Thinking Molecules and Nanodiagnostics

Wet nano is expanding so fast that in some areas it's going dry. A good example is molecular computing. Think back to the 1953 Watson-Crick model of the double helix — which graphically demonstrates that a living gene is at its core information. Life, in other words, is synonymous with data.

DNA is designed to store vast quantities of data, and natural enzymes can manipulate this information. Essentially, DNA-based computing would abandon the linear processing current computers use for a more parallel approach involving solving many small tasks at a time.

Similar advances will be made in nanodiagnostics. Consider the work being done at the University of Calgary in Canada. There, a laboratory team is using nanoscience to reduce the amount of medical test samples needed from milliliters to femtoliters — a far smaller measure.

Tests on large samples tend to be slow and costly. Testing smaller samples will save money and make testing more readily available. ■

Fullerenes, Buckyballs and Hundred-Mile Elevators

The biggest news in nanotech today is grunge. Filth. Crud. The soft, black, fine-grained stuff that smears your hands when you clean a car engine, a kerosene lantern or a wood-burning fireplace. It's found everywhere an organic substance has been burned, and has an Anglo-Saxon name unchanged in centuries: soot. Strangely enough, new products based on this humble substance have spun off some of the most commercially advanced sub-sectors in nanotechnology.

The Chemistry of Carbon

Soot has been part of human life since we harnessed fire. We may have streaked our faces with it when we went to battle. Soot antedates humanity. It's 100 percent carbon, atomic number 6 — and life on earth is based on it. Soot is literally in our genes.

Soot also underlies a lot of current nanotechnology. Carbon atoms are gregarious little guys. They stick to almost everything — including themselves — using something called a covalent bond. Atoms bond by sharing an electron. Covalent bonds involve two electrons. The double dose of cement makes them fast to make and hard to break. Carbon allotropes such as soot are so stable they can stay as they are forever.

The chemistry of carbon is central to life. Imagine six atoms in a long string, every other pair snugly coupled with a covalent bond. Bend the string so that it forms a ring, cement the ends, and you have a six-sided loop called a benzene ring, which is the linchpin of organic chemistry.

Many drugs are based on the benzene ring because each angle of the hexagon provides an attachment point for medically useful stuff. The problem is that the bonds between neighbors aren't rigid even if they are strong, and the ring can bend and twist out of shape. This can reduce the medication's effectiveness.

Enter carbon nanotechnology with a set of molecular allotropes called fullerenes. It all started with an American engineer named R. Buckminster Fuller sixty years ago. He observed that a great many monuments had as a design feature ornamental cannonballs arranged

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Fullerenes, Buckyballs and Hundred-Mile Elevators

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in various ways. Bucky wondered what shape would result if the balls were stacked and arranged in the way that used the minimum volume.

The answer was what we know today as a geodesic sphere. A practical example of his discovery is the geodesic dome — a structure that supports itself rather than requiring internal supports.

It turns out that what Buckminster Fuller did with artificial spheres like cannonballs, nature has already done with carbon atoms. Soot atoms can spontaneously arrange themselves into structures like the U.S. Pavilion at Expo 67 in Montreal — a geodesic dome sixty yards in diameter. These carbon allotropes are called buckminsterfullerenes — abbreviated to "buckyballs." A buckyball molecule looks like a soccer ball.

Implications of the Buckyball

If a benzene ring can deliver drugs, then a buckyball should do even better. A buckyball is strong and stable and could in theory deliver treatments with greater efficiency and more consistent effects. A lot of bio-nano start-ups and giant biopharm multinationals think so and they are betting millions of dollars on their predictions. Currently under development are buckyball drugs for HIV infections, treatment of Lou Gehrig's disease, and cancer.

Stronger than Spiderwebs

Carbon materials offer us the opportunity of building things taller, wider, stronger and safer than anything we have attempted before. The key to all this is the single-walled buckytube. It's twice as strong as spider web silk, which in turn is 100 times stronger than bridge-grade steel. A carbon fiber cable two millimeters in diameter – the width of a ballpoint pen refill – could support twenty tons and not come close to its theoretical breaking point. At 25 tons, it would still be loafing. That is because buckytubes' actual strength comes far closer to ideal values than most other materials can manage.

To fulfill soot's structural promise, nanoscientists who would be nanopreneurs must first grow buckytubes far longer than they have yet done. But once that has been accomplished, a cable the thickness of a pencil should be able to support the Brooklyn Bridge. Entirely new species of bridges, buildings and aircraft will soar aloft with no visible means of support. Untearable fabrics, hair-thin auto bodies and nonpierceable body armor for police and the military will all appear.

Equally promising is what happens when you take a fullerene and unzip it at one or both poles. This is a buckytube. Discovered in 1991 by Dr. Sumio Iijima, buckytubes may be covered by one or more layers of carbon atom sheathing. IBM has used the concept to begin developing transistors for use in computing. Possible in the future are elevators based on buckytubes that can launch satellites into space by walking them up a giant ladder rather than rocketing them aloft. More practical applications today include flat-screen, ultra-thin video monitors. Within the next few years we may see television screens no deeper than a coat of paint. ■

Nano-Pitfalls

Those in the nanocosm who believe they can build a molecular assembler or nanobot — K. Eric Drexler, for example — may find that the process will be impossibly complicated. As Dr. Drexler imagines it, nanomachinery is staggeringly intricate. But that's not the worst of it. Actually running such an animal will be even harder. To function, a Drexlerian nanobot would have to first store high-level instructional software onboard in large quantity. And to work as the Drexlerians want, the nanobot would also have to distinguish among many possible conditions, materials and configurations and then act instantly and appropriately in every case. It would have to sense distances to subangstrom accuracy and act in shavings of a picosecond. Given the absurdly tight dimensional constraints, there would be literally no room for error.

A nanobot that fit into a 50 nanometer cube might require half a billion lines of ROM software, permanently embedded somewhere in its unthinkably minuscule frame. Dr. Drexler and his acolytes speculate about how these data might be encoded. Even molecular memory would be too clunky for a working nanobot. This just won't happen. Engineers can't bend nature to the extent required to make it all work. It is hubris to think it could.

Real nanotechnology, as opposed to the boosters' sci-fi speculations, will continue to be advanced by rigorous experiment and careful theory from such classical disciplines as physics, materials science and chemistry.

Does this mean nanoscience won't bring us astonishing discoveries, or nanotech a parade of amazing new products? Not at all. Our new ability to see the nanocosm, to get it to assemble itself to our detailed specifications, will shortly create the most profound changes since our ancestors tamed fire. Stay tune: it's going to be one wild ride. ■

For Additional Information on a list of the kinds of advances we can expect in the next decades, go to: http://my.summary.com