Bridges to Safety, and Bridges to Progress

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Abstract

Advanced nanotechnology offers unprecedented opportunities for progress—defeating poverty, starvation, and disease, opening up outer space, and expanding human capacities. But it also brings unprecedented risks—massive job displacement causing economic and social disruption, threats to civil liberties from ubiquitous surveillance, and the specter of devastating wars fought with far more powerful weapons of mass destruction.

The challenge of achieving the goals and managing the risks of nanotechnology requires more than just brilliant molecular engineering. In addition to scientific and technical ingenuity, other disciplines and talents will be vitally important. No single approach will solve all problems or address all needs. The only answer is a collective answer, and that will demand an unprecedented collaboration—a network of leaders in business, government, academia, and NGOs. It will require participation from people of many nations, cultures, languages, and belief systems.

Never before have we faced such a tremendous opportunity—and never before have the risks been so great. We must begin building bridges that will lead to safety and progress for the entire world; bridges that will develop common understanding, create lines of communication, and create a stable structure that will enable humankind to pass safely through the transition into the nano era.

Introduction

Information technology, cognitive science, biotechnology, environmental science, aerospace technology—all will have significant impacts on society over the next two decades. Each will provide bridges to progress, and some will raise concerns about safety.

But the most difficult challenges likely will result from exponential general-purpose molecular manufacturing, made possible by advanced nanotechnology. This could have far-ranging environmental, economic, military, ethical, legal, and social implications.

Nanotechnology is expected to have great impacts on many fields, including mining, refining, manufacturing, transportation, storage, and wholesale and retail distribution. It could mean millions of jobs lost, or shifted. It could represent a radical transformation of traditional power structures, which may not come about easily, or peacefully. It could also mean opportunities like we've never had before to relieve poverty, prevent illness, and offer education to millions of people in developing nations.

In what areas will nanotechnology have the greatest impact? What nations or corporations are working to develop it? How soon should all these impacts be expected? What policy choices can be made today that may change the anticipated outcomes?

Unfortunately, we do not have conclusive answers to all these questions. Much more research is needed. In this paper, we'll provide a current overview of the issues, the facts, and our future prospects as we approach the era of nanotechnology.

The Meaning and Impact of Nanotechnology

Virtually every previous technological improvement has been accomplished by making things smaller and more precise. But as the scales at which we work get smaller and smaller, we approach limits imposed by physics. The smallest unit of matter we can build with is the atom, or combinations of atoms known as molecules. The earthshaking insight of nanotechnology is that, when we reach this scale, we can reverse direction and begin building from the bottom up, making products by placing individual atoms and molecules exactly where we want them.

Nanotechnology has several meanings and encompasses many fields. The National Science Foundation defines it as: "Research and technology development in the length scale of approximately 1 to 100 nanometers." By this loose definition, some types of nanotechnology exist already, producing specialized materials and components including powders, films, and chemicals. Not spectacular, perhaps, but attractive to investors because many products will be improved significantly.

Progress in this basic area will enable the more transformative kind of nanotechnology, known as *molecular manufacturing*—combining chemistry and fabrication to produce precise machines and manufacturing systems at the nanometer scale. This is the most promising, threatening, and controversial aspect of nanotechnology.

A recent report prepared for NATO (Ibrügger, 2001) said, "Theoretical and computational models indicate that molecular manufacturing systems are possible—that they do not violate existing physical laws. These models also give us a feel for what a molecular manufacturing system might look like. Today, scientists are devising numerous tools and techniques that will be needed to transform nanotechnology from computer models into reality. While most remain in the realm of theory, there appears to be no fundamental barrier to their development."

The fundamental ideas for molecular manufacturing were introduced more than 40 years ago in a famous talk titled "There's Plenty of Room at the Bottom" (Feynman, 1959). In this speech, Nobel prize-winning physicist Richard Feynman said, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom."

Feynman also said, “I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously.” That’s exactly the way today’s leading theorists (Phoenix, 2003) plan to build things from the bottom up—by using billions of identical tiny machines, all operating in parallel under external computer control. It’s a startlingly original concept called a *nanofactory*, and it seems to be coming close to reality.

Until recently, it has been assumed that although molecular manufacturing will be developed eventually, the extreme technical challenges place it far in the future, perhaps 30 to 50 years away. Now, however, several estimates of technical feasibility conclude that a time frame of 2010 to 2015 is a plausible estimate for the development of nanofactories.

As today’s nanotechnology steadily advances to the point that large-scale manufacturing becomes possible with atomic precision and virtually no waste—then things will rapidly change. Working directly with atoms, even a small portable manufacturing system could contain the equipment to duplicate itself on command as cheaply as building any other product. This leads to *exponential dispersion of customized manufacturing capability*.

Portable, programmable manufacturing systems—nanofactories—will revolutionize commerce and industry, and by extension, all of society, but probably not without negative effects. There are both benefits and dangers at hand, and as we build bridges to progress, we must also build bridges to safety.

Unprecedented Opportunities for Progress

Nanotechnology is called a *general-purpose* technology, because it will have significant impact on almost all industries and all areas of society. It offers better built, longer lasting, cleaner, safer, and smarter products for the home, for communications, for medicine, for transportation, for agriculture, and for industry in general.

> *Imagine a medical device that travels through the human body to seek out and destroy small clusters of cancerous cells before they can spread. Or a box no larger than a sugar cube that contains the entire contents of the Library of Congress. Or materials much lighter than steel that possess ten times as much strength.* — U.S. National Science Foundation website

Enthusiasts envision using nanotechnology to build space elevators, mine the asteroids, clean up the environment, end hunger and poverty, and even go inside the human body to offer extreme health extension, memory and intelligence augmentation, or a direct mind-computer connection. Some of these capabilities may be exaggerated; the difficulties that will confront developers, both in achieving technical goals and in managing unwanted side effects, often are minimized or dismissed entirely. However, it's almost impossible to overstate the beneficial potential of molecular manufacturing.

Almost overnight, advanced nanotechnology could solve many of the humanity's chronic problems. Simple products like plumbing, water filters, and mosquito nets—made cheaply on the spot—could greatly reduce the spread of infectious diseases. The efficient, cheap construction of light, strong structures, electrical equipment, and power storage devices will allow the use of solar power as a primary and abundant energy source.

Many parts of the world could not sustainably support a 20th-century manufacturing infrastructure, with its attendant environmental and societal impacts, but nanofactory manufacturing would be self-contained, cheap, and clean. A single packing crate or suitcase could contain all the equipment required for a village-scale industrial revolution.

Computers will become stunningly inexpensive and could be made widely available, improving communication, education, and government accountability. Much social unrest can be traced directly to material poverty, ill health, and ignorance. Nanofactories can greatly reduce these problems.

Effects on Traditional Industries

Like electricity and computing before it, nanotechnology will offer greatly improved efficiency in almost every facet of life. But as a general-purpose technology, it will be *dual-use*, meaning it will have many commercial uses and it also will have many military uses—making far more powerful weapons and tools of surveillance. Thus, it represents not only wonderful benefits for humanity, but also grave risks.

Before discussing geopolitical implications, we will first consider potential negative impacts on our current economic structure.

Josh Wolfe of Lux Capital, editor of the *Forbes/Wolfe Nanotech Report*, says, "Quite simply, the world is about to be rebuilt (and improved) from the atom up. That means tens of trillions of dollars to be spent on everything: clothing, food, cars, housing, medicine, the devices we use to communicate and recreate, the quality of the air we breathe, and the water we drink—all are about to undergo profound and fundamental change. And as a result, so will the socio and economic structure of the world. Nanotechnology will shake up just about every business on the planet."

Low-cost local manufacturing and duplication of designs could lead to economic upheaval, as major economic sectors contract or even collapse. To give one example, the global steel industry is worth over $700 billion. What will happen to the millions of jobs associated with that industry—and to the capital supporting it—when materials many times stronger than steel can be produced quickly and cheaply wherever they are needed?

Advanced nanotechnology could make solar power a realistic and preferable alternative to traditional energy sources. Around the world, individual energy consumers pay over $600 billion a year for utility bills and fuel supplies. Commercial and industrial use drives the figures higher still. When much of this spending can be permanently replaced with off-grid solar energy, many more jobs will be displaced.

The worldwide semiconductor industry produces annual billings of over $150 billion. The U.S. Bureau of Labor Statistics reports that the industry employs a domestic workforce of nearly 300,000 people. Additionally, U.S. retail distribution of electronics products amounts to almost $300 billion annually. All of these areas will be significantly impacted if customized electronics products can be produced at home for about dollar a pound, the likely cost of raw materials. If molecular manufacturing allows any individual to make products containing computing power a million times greater than today's PCs, where will those jobs go?

Other nations will be affected as well. For example, the Chinese government may welcome the advent of exponential general-purpose molecular manufacturing for several reasons, including its potential to radically reduce poverty and reduce catastrophic environmental problems. But at the same time, China relies on foreign direct investment (FDI) of over $40 billion annually for much of its current economic strength. When those dollars to purchase Chinese manufactured goods stop flowing in, the required adjustments may not be easy and could result in violent struggles.

Geopolitical Instability

We've reviewed the earthshaking impacts that molecular manufacturing is likely to have on business, investment, jobs, and, by extension, social stability. Geopolitical implications also must be considered. This technology may enable individual nations to achieve complete economic independence. Coupling that with the potential for rapid augmentation of offensive military power leads to the unsettling possibility of devastating warfare.

In today's world, even though each nation is politically independent, they all rely to some degree on other nations for trade or security, or both. No nation—at least no nation of even minimal significance—exists free from this interdependence. But molecular manufacturing has the potential to change all that, and not for the better.

When individual countries are able to provide all their own goods and services, and no longer have need for import or export trade, they will have less incentive to maintain good relations with others. When economic security is no longer an issue, the only remaining security concern will be military.

Now we have all the makings of a terrible new arms race. Every country possessing unrestricted molecular manufacturing capability will have the ability to design, test, and stockpile massive amounts of small, cheap, frighteningly powerful weapons. Assuming that nanotechnology development is allowed to proliferate, we can expect that many countries will achieve economic independence and unprecedented military prowess.

Will we then see a stable equilibrium, a tenuous balance of power similar to the "mutually assured destruction" of the Cold War? Not likely. Nuclear weapons require massive research effort and industrial development, which can be tracked far more easily than nanotech weapons development. Molecular manufacturing will enable nanotech weapons to be developed much more rapidly due to faster, cheaper prototyping. It will be nearly impossible to know with any certainty how much war-making capability your enemy, or your neighbor, possesses.

Less response time to an attack, and better-targeted destruction of the enemy's resources during an attack, will make these new arms races highly unstable. Unless nanotechnology is tightly controlled, the number of nanotech-possessing nations in the world could be much higher than the number of nuclear nations, increasing the chance of a regional conflict blowing up. Greater uncertainty of the capabilities of the adversary could promote caution—but could also increase the temptation for preemptive strikes to prevent proliferation.

Worse still, this opens the door for the development of rival groups within countries. We might see repeated military coups, devastating civil wars, and dissolution of nations into large numbers of hostile, unpredictable, immensely powerful tribes. Another concern is that radical transnational groups bound by religious, cultural, or ideological extremism might make use of molecular manufacturing toward terrorist ends.

Is Relinquishment an Option?

Approached with pessimism, nanotechnology appears far too dangerous to be allowed to progress to anywhere near its full potential. It's tempting to just say no, to urge that we shut Pandora's Box and halt further development.

The possibility of technological relinquishment was made famous by computer scientist Bill Joy in his article, "Why the Future Doesn't Need Us" (Joy, 2000). Joy saw great danger to the continued existence of the human race from nanotechnology (as well as from robotics and genetics). He advocated an enforced global relinquishment of so-called "dangerous technologies," which essentially would require an end to further development of almost all new technology.

Although Joy's call met with some support from environmental activists and a few others, the overwhelming consensus reaction was highly skeptical of both the feasibility and the advisability of such a shutdown. For one thing, it will almost certainly be impossible to prevent the development of molecular manufacturing technology somewhere in the world. China, Europe, and Japan all have thriving nanotechnology programs, and the rapid advance of enabling technologies such as biotechnology, MEMS, and scanning-probe microscopy ensures that nanotechnology research and development efforts will be much easier in the near future than they are today.

Perhaps the strongest argument against relinquishment is the loss or delay of immense benefits. The great promise of molecular manufacturing is the potential to reduce stress on the environment, to alleviate most shortages, to raise living standards worldwide, to eradicate nearly all poverty, starvation, and homelessness. Molecular manufacturing can greatly aid in providing clean drinking water, effective sanitation, and protection from many infectious diseases. Clean, cheap, and efficient manufacturing; medical breakthroughs; immensely powerful computers; easier access to space—all these benefits are simply too good to pass up.

The Time to Prepare is Now

The barriers to a successful molecular manufacturing development project may already be surprisingly low. The challenge is mainly engineering, not unpredictable scientific breakthroughs. The primary technical barriers are the lack of a detailed design and the need for a better understanding of the required laboratory techniques. Both of these problems should be solvable with sufficient resources, and significant progress is steadily being made.

Large-scale nanotech manufacturing depends on programmable chemical fabrication of structures, followed by assembly of these structures to make larger systems. This has been studied intensively on a theoretical level. Assuming the theory works—and no one has discovered a problem with it yet—exponential general-purpose molecular manufacturing appears to be inevitable. It might be become a reality by 2010, likely will by 2015, and almost certainly will by 2020.

Recent research (Toth-Fejel, 2004) has found that the design of a self-fabricating system might be simpler than a desktop computer's CPU. An automated, self-contained factory could build lifesaving medical robots—or untraceable weapons of mass destruction. For less than a million dollars, it could build networked computers for everyone in the world—and for another million, networked cameras so governments can watch our every move. These factories will create trillions of dollars of abundance—and a vicious scramble to own it. Cheap rapid prototyping will enable rapid invention of wondrous products—and weapons development fast enough to destabilize any arms race.

Along with sizable benefits, the technology brings serious challenges. Analysis by the nonprofit Center for Responsible Nanotechnology (CRN), a think tank co-founded by the author, shows that numerous severe problems could spiral out of control before today's existing institutions would have time to react. Reactive development and application of molecular manufacturing policy almost certainly will be insufficient.

Attempts to control these problems may lead to abusive restrictions, or create a black market that would be very risky and almost impossible to stop; small nanofactories will be very easy to smuggle, and fully dangerous. Efforts to preempt malicious or unauthorized use of the technology could result in threats to civil liberties from constant intrusive surveillance.

Without advance planning—without wise and well-informed policy—we will walk blindly off a cliff. Bad policy will lead to mushrooming problems, which will inspire more bad policy. In the struggle between anarchy and oppression, the one sure loser will be “we the people.”

Never before has humanity faced such a tremendous opportunity—and never before have the risks been so great. We must begin now to build those bridges that will take us beyond the cliffs and safely into the nano era.

The Challenge We Face

The challenge of achieving the goals and managing the risks of nanotechnology requires more than just brilliant molecular engineering. In addition to scientific and technical ingenuity, other disciplines and talents will be vitally important. Chemists, political scientists, physicists, lawyers, engineers, economists, sociologists, medical doctors, ecologists, and ethicists will need to work together to ask and answer the right questions.

No single approach will solve all problems or address all needs. There are numerous severe risks—including several different kinds of risk—which cannot all be prevented with the same approach. Simple solutions won't work.

The only answer is a collective answer, and that will demand an unprecedented collaboration—a network of leaders in business, government, academia, and NGOs. It will require participation from people of many nations, cultures, languages, and belief systems.

Some solutions already have been proposed. For example, CRN issued a study (Treder and Phoenix, 2003) proposing an international networked structure to oversee the safe development and effective administration of molecular manufacturing. More recently, on the Wise-Nano.org collaborative online research project, a treaty organization, the International Nanotechnology Research Consortium (Craver, 2004), was proposed.

Implementing a solution of this magnitude will be anything but easy. If one of these solutions is found to be the right answer, it must be undertaken right away. And if they are not the right solutions, we must determine something better as soon as possible.

The high stakes will tempt many to shrink from the challenge—even to declare all this to be impossible. But wishful thinking cannot make either turbulence or technology disappear. Further policy research is urgently needed.

Our task now is to begin building bridges that will lead to safety and progress for the entire world; bridges that will develop common understanding, create lines of communication, and create a stable structure that will enable humankind to pass safely through the transition into the nano era.

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