Challenges and Pitfalls of Exponential Manufacturing

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These early years of the 21st century already are a time of rapid advances in science and technology. Every day brings news of startling developments in fields such as genetic engineering, neuroscience, and nanotechnology. So what *will* the near future actually bring us? Human beings that glow in the dark, like our bioengineered pets? Robot servants? Flying cars? Genuine artificial intelligence? Or something even more exotic?

There is good reason to believe that within the next 10 to 20 years, the most significant changes to society will go far beyond glowing people or flying cars. Many of them may result from the introduction of *personal nanofactories*, a powerful application of exponential general-purpose molecular manufacturing, made possible by advanced nanotechnology.

In this paper, we will explain exponential general-purpose molecular manufacturing: the basic concepts behind it, and why it will be a technological breakthrough of transformative power. We will show why preparing for it is vitally important—*and* will be very difficult. Along the way, we will explore how several types of social systems may respond to the changes that molecular manufacturing will bring, including unprecedented material abundance and other opportunities. We will take a brief look at the possible timeline (sooner than many people will expect), explore problems in familiar areas such as military conflict, and touch on new classes of problems that humanity will have to face. By the end, it should be clear that the challenges and opportunities created by molecular manufacturing cannot be addressed by any simple solution.

MOLECULAR MANUFACTURING

"Exponential general-purpose molecular manufacturing"—let's take this big phrase apart to see what it means and why it is so important.

- MANUFACTURING: The ability to make products, in this case ranging from clothing, to electronics, to medical devices, to books, to building materials, and much more.
- MOLECULAR manufacturing: The automated building of products from the bottom up, molecule by molecule, with atomic precision, using molecular-scale tools. This will make products that are extremely lightweight, flexible, durable, and potentially very "smart."
- GENERAL-PURPOSE molecular manufacturing: A manufacturing technology that will find many applications across many segments of society. Its extreme flexibility, precision, high capacity, and low cost will cause rapid adoption almost everywhere, and therefore will have disruptive effects in many industries.
- EXPONENTIAL general-purpose molecular manufacturing: The word 'exponential' refers to the rapid pace—probably unprecedented—at which this technology may be

deployed. A compact, automated molecular manufacturing system will be able to make *more* manufacturing systems; we are talking about factories that can build duplicate factories—and do it in less than a single day. The math is simple: if one factory makes two, and two factories make four, then within ten days you could have one thousand factories, in ten more days a million factories, and ten days after that a *billion* factories. Within the span of just a few weeks, in theory, every household in the world could have one of their own to make most of the products they need at just the cost of raw materials.

Exponential general-purpose molecular manufacturing means a manufacturing system—a personal nanofactory—capable of making a wide range of technologically advanced products, far superior to what we have today, much cheaper, much faster, and able to multiply its own source of production exponentially.

The consequences of this are mind-boggling, to say the least. It could mean the drastic restructuring of whole industries, including mining, refining, 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 have never had before to relieve poverty, prevent illness, and offer education to millions of people in developing nations.

Imagine the economic value in possessing such a revolutionary technology. Imagine the military advantages it would offer. How much would a government, or even a rich and powerful corporation, pay to possess molecular manufacturing? We do not know for sure whether it would take $10 billion USD, $1 billion USD, or even less to begin developing it today, but by 2020 it may require as little as $10 million USD. This is because many of the required capabilities are being developed rapidly in other technologies. And exponential general-purpose molecular manufacturing obviously would be worth at least hundreds of billions of dollars, and perhaps hundreds of trillions. It is only a matter of time before the technology arrives, and when it does, the consequences could be staggering.

If made widely available at low cost (the raw materials should be very cheap), personal nanofactories could solve many of the world's problems. Simple products like plumbing, water filters, and mosquito nets—made on the spot—would greatly reduce the spread of infectious diseases. The efficient, inexpensive construction of strong and lightweight structures, electrical equipment, and power storage devices would allow the use of solar power as a primary and abundant energy source. Computers and display devices could become stunningly inexpensive and available to nearly everyone. Much social unrest can be traced directly to material poverty, ill health, and ignorance. Molecular manufacturing could greatly reduce these problems, but only if it is wisely administered.

If corporations or governments try too hard to restrict distribution, and legitimate access is not provided, a black market will quickly develop. The risk here is that unauthorized nanofactories may not have the necessary safety measures built in. All sorts of dangerous products—from weapons to poisons to microscopic surveillance devices—could be made at low cost in mass quantities. To complicate matters, tiny manufacturing systems could be used to make bigger ones, and each large one could make thousands of duplicates. Smuggling of these systems would be impossible to prevent. Some solution will have to be found.

It is impossible to overestimate the effects these developments may have on society and on our individual lives. Informed preparation is essential.

EXPANDING RESOURCES

Now that we have introduced the concept of personal nanofactories, let’s take a different approach to try and understand the implications and the challenges brought on by such a transformative technology.

Most people have certain possessions that could easily be sold if the price is right, and others that would not be sold under any normal circumstances. For example, one's bookshelves may contain paperback fiction, photo albums, and old textbooks that haven't been opened in a decade or two. Photo albums are not normally sold—their sentimental value to the owner is far higher than their value to anyone else. Mass-market paperbacks, on the other hand, can easily be replaced, and might be sold to any visitor who values them more than the current owner. A visitor who asked to buy one's personal photo albums would likely be met with suspicion and even hostility.

Sentimental value is not the only reason for keeping possessions off the market; things that are important to survival will not be sold except in very unusual circumstances. Also, individuals are not the only entities that recognize the distinction between saleable and protected items. Whereas people may cheerfully sell a plot of land, a nation will be very unlikely to permanently shrink its borders for mere money.

The goal of commerce is to help trades happen easily and efficiently, since every voluntary trade enriches both parties (at least according to economic theory). By contrast, for resources that must be protected, the goal is to prevent any transactions from taking place—to maintain the status quo. The reason is that any transaction will reduce the sum total value of the objects that change hands.

Achieving such different goals might be expected to require rather different types of institutional approaches. In fact, the author Jane Jacobs has observed exactly that. In *Systems of Survival,*[1] she describes two different systems of institutional ethics, 'Guardian' and 'Commercial.' Studying how these systems have developed, she describes a number of sharply contrasting rules. For example, Guardians traditionally shun trade, while Commercials of course exist for trade. Guardians are allowed to deceive, while Commercials should be honest.

Now think back to the bookshelf that provided our first example. There was a third kind of book on the shelf: a book containing useful information (a textbook) that the owner nevertheless did not need. In such a case, the owner could go to the bother of trying to sell the book, but there is another alternative. It may be preferable simply to give the book away—to donate it to some place where it will be found by someone who can use it.

A physical book can only be in one place at a time, but information has no such restriction. And although some information is most valuable when kept secret, a lot of information grows in total value as it is shared. All that remains is to make sharing easy and rewarding, and the information can spread from its originator almost indefinitely, providing benefit without any fixed limit.

Thanks to computers and the Internet, sharing information is far easier than it has ever been. In many parts of the world, information in gigabyte quantities is literally too cheap to meter—there is no incremental cost for sharing or receiving almost any data file. In the centuries before computers, great scientists and artists made their creations available to the world, and sufficiently valuable information was copied widely—by hand, if necessary. But today, it is not only the great information that is worth sharing. Near-trivial observations, computer programs, and works of art are shared over the Internet—and thanks to modern search engines, the valuable fraction can be found and used.

The ethic of sharing information, or the 'Informational' system, is different again from the Guardian and Commercial systems. As in the Guardian system, financial compensation is discouraged; as in the Commercial system, the use of force is also discouraged. Whereas Guardians can lie to achieve their aims and Commercials can conceal information, the Informational system works best with not just honesty but with openness.

The Guardian system is essential, obviously, to guarantee a group's survival, but it operates on a *zero-sum* basis, meaning that the assets of one group are not voluntarily traded with another group. Rather, they are protected, even hoarded. If one entity wants something another has, it must be taken by force. The total sum of what is available does not grow due to this style of exchange between groups: it remains static, or even decreases, as when a stolen automobile is broken up for spare parts. Hence, *zero-sum* is a reasonable description of the (lack of) potential for expansion of assets.

By contrast, the Commercial system allows groups to increase the value of their possessions by augmenting them through trade. A tribe or corporation with a surplus of goods can exchange some of what they have with another tribe or company who has something the first group needs. As a result, both parties are better off than they were before. This system is therefore considered win-win, or *positive-sum*, because the potential exists for everyone to gain.

Now that even modestly valuable things that can be duplicated at near-zero cost, the Informational system is becoming increasingly important. The Open Source software movement has produced large, high-quality, valuable pieces of software, including an entire computer operating system—and given them away, simply because so many people found it worthwhile to work on the projects and then share their work to be used by whoever could benefit. One of the ethics of the Informational system is that the creator's name should accompany their creation, so that their reputation will be enhanced.

The Informational system is neither altruism, nor communism, nor charity. Creation and discovery are fun—just ask any child with finger paints, or any backyard astronomer. Sharing one's creations is also fun, especially when the result is recognition and reputation. Whereas communism is an inefficient system for redistributing scarce resources, the Informational system is a very efficient system for distributing resources that are fundamentally non-scarce. There is no obligation to share any given piece of information, any more than a person is obliged to sell or give away any of their possessions. It is worth stressing this point, because those new to the Informational system frequently confuse it with coercive scarcity-based systems. The Informational system is not suitable for scarce physical goods, but when applied to information that can be shared to virtually unlimited extent at virtually no cost to anyone, the Informational system can lead to an *unlimited-sum* outcome.

Just as the Informational system is inappropriate in many situations, so too are the Guardian and Commercial systems. A retail store that viewed its customers with Guardian suspicion and its stock with Guardian possessiveness would waste so many opportunities that it would quickly go out of business. A person or other entity that was willing to sell its basis of survival for short-term financial gain would quickly cease to exist. Likewise, even though the free market is an excellent system for allocating naturally scarce resources, imposing artificial scarcity on information in order to treat it commercially can lead to massive and tragic loss of opportunity.

Applying the wrong system can cause either lost opportunities or wasteful dissipation, but mixing the systems incautiously is at least as bad. The ethics of each system are too dissimilar; an organization that tries to follow a combination of approaches will find itself led in opposite directions. The result will either be paralysis or excessive license. The results are so bad that Jane Jacobs calls such mixed systems "monstrous moral hybrids," giving examples of the Mafia, the Third Reich, and Communism.[2]

How might we expect various organizations that follow one of these three systems of community action to respond to the transformative impacts of nanofactory technology? Before answering that, let's take a closer look at just how disruptive those effects could become.

EFFECTS: GOOD, BAD, AND UGLY

Molecular manufacturing will be an extremely powerful technology, with a wide range of possible effects. Some of the effects are good, such as inexpensive local manufacture of humanitarian relief supplies. Many of the effects are bad, including the widespread availability of untraceable, highly advanced weapons. Some products of molecular manufacturing may be either good or bad, depending on how they are used; examples include surveillance equipment and space flight hardware. Any of several different competitions could have extremely negative effects, such as a rapid and unstable arms race leading to war.

Given a portable, self-contained, self-building factory system that can make a wide range of products directly from blueprints in essentially unlimited quantities, it should not be difficult to design and rapidly construct new products, whenever and wherever desired. An explosion of creativity similar to the World Wide Web could develop quickly.

The good news is that general-purpose exponential manufacturing could create a level of low-cost abundance far beyond the capabilities of any present-day economy. If distributed wisely, this abundance and its accompanying security could reduce present-day sources of conflict. However, as we will see in the next section, wise distribution of resources is not easy. There are a number of reasons why the hoped-for abundance may not be developed or may not have the desired effects.

The bad news is that rapid development and availability of new products could include new kinds of weapons. Arms races could develop almost overnight, with each side (whether a nation or a smaller group) rapidly countering the other's previous advances. Due to several factors, such an arms race would likely be unstable and lead quickly to open conflict. On a large scale, such conflict could be devastating, perhaps even threatening the survival of civilization; even on a smaller scale, it could represent a terrible risk. There may even be a danger that a nihilistic or genocidal group or person could do irreparable damage on a global scale single-handedly, using only modest resources. It is too early to tell whether or not the capability to build tons of milligram-scale antipersonnel weapons will be widely available, but such discomforting scenarios must be taken seriously and carefully analyzed.

As we will see in the next section, the issues raised by molecular manufacturing include several extremes that appear to be opposites: oppressive control vs. anarchic destruction, unbridled hedonistic consumption vs. crushing scarcity. In fact, however, these are not mutually exclusive; they may be concurrent and may reinforce each other. Avoiding such an outcome will not be easy.

ORGANIZATIONAL RESPONSES

A technology that can be copied at will, and that can produce a wide range of valuable products out of nothing but information, energy, and simple raw materials, will naturally spread widely unless something or someone actively prevents it. A number of organizations will want to do just that.

Security/Guardian organizations will want to limit availability of destructive technology, while preserving for themselves the means to damage their enemies. A manufacturing technology that could quickly produce any weapon downloaded from the Internet would be a major security threat, especially when the weapons could contain enough "smarts" to be used remotely in time and space from the attacker. Crime requires means, motive, and opportunity, all of which have imposed limits on criminality; however, possession of a nanofactory would provide the means and opportunity to do almost anything. Although new defenses would surely be developed, this would not be a lot of comfort to a Guardian contemplating a continuing stream of new weapon designs. Thus, it seems clear that Guardians will have a strong incentive to restrict private availability of the technology.

But even if private ownership of nanofactories were forbidden by law, this would not solve the security problems. Illegal ownership might develop—it only takes one nanofactory to make thousands more, and they could be made quite concealable. Either a stolen nanofactory, or an independent development project (which will rapidly become easier to achieve), could put the first nanofactory into private hands. Finally, even if private ownership of nanofactories were made impossible (which almost certainly would require draconian levels of repression), arms races between national militaries would likely still lead to war.

Commercial groups also may have an incentive to limit the availability of nanofactories. If products of personal nanofactories are abundant and inexpensive, it may be difficult to make a large profit by selling stuff—or at least, this will be the fear of many existing Commercial interests. That this may not necessarily be the case is shown by examples from the entertainment and software industries. The movie industry fought against the introduction of VCRs, but as it turned out, video rentals form a major revenue stream today. And while patents are widely considered to be necessary to support innovation, software patents did not exist until the mid-1980's—years after the development of Unix, the IBM PC, the Apple Macintosh, and the Internet.

Extremes of communism and capitalism are both likely to be sub-optimal. Although it may be tempting to think that such a radical shift in the economics of production could finally allow communism to work, the reasons why communism failed go beyond the economic context. Setting by fiat the resources allocated to a person—whether above or below what they have earned—turns out to be intensely demotivating, and the result is wasted opportunity and societal depression. On the other hand, with capitalism, the vast disparity between cost of production and value of product, combined with the reduced value of labor, would cause nearly instant and total concentration of wealth, impoverishing the vast majority of people.

The Informational system appears to be an excellent fit for some aspects of molecular manufacturing. Nanofactory blueprint files could be transferred and modified as easily as software programs or other types of information. The Open Source software movement demonstrates that some people are eager to spend thousands of hours developing a product that they intend to give away without financial compensation; it seems likely that nanofactory product development could proceed successfully along similar lines. There is no obvious reason why an Informational approach would want to restrict nanofactories; on the contrary, that approach would work best if nanofactories were available to all without restriction.

A combination of Informational and Commercial options (though not necessarily combining both styles in any single organization) may turn out to be the optimal way to deliver the benefits of molecular manufacturing. To the extent that nanofactory blueprint development is similar to software development, history shows that this approach can work quite well for all concerned. Commercial software products tend to be more user-friendly, because money is invested in making what the customer wants, not what is fun for the programmers to write. As a result, even the free products of the Open Source movement cannot out-compete commercial products. At the same time, free products are available for those who cannot afford commercial software. Meanwhile, the commercial software industry benefits from the creative ideas of the independent Informational creators who do not have to conform to business plans or conventional wisdom.

If a similar system were implemented for molecular manufacturing, it might look like this: Nanofactories are available for free, or nearly free. Commercial designs are protected by a variety of legal and technical mechanisms. At the same time, the necessities of life are available to anyone, not by charity or by law, but simply because some hobbyist who wanted their designs widely used had made them available at no cost. In this scenario, no one has to be impoverished to the point of damaging their physical security; however, those who want luxury products would have to pay for them, thus maintaining a structure of commercial incentives. (It is not yet known whether this system would improve security, due to distributed development of technologies of defense and accountability, or damage security due to widespread availability of the means to do harm.)

WHERE, WHEN, WHAT, AND HOW?

Much will depend on how quickly and by whom molecular manufacturing is developed. If the technology matures slowly—and openly—over the next 15 or 20 years, there may be time to adjust with relatively little disruption. If it is developed many more years in the future, its effects may be muted by other technologies. However, if it is developed rapidly and soon, it could be quite disruptive, even dangerous.

Molecular manufacturing will work by a synergy of several technologies that are individually fairly mundane. It will require only a few different manufacturing operations that can be performed many times in programmed automated sequence. These operations will, bit by bit, build products out of atoms, just as your body builds proteins by fastening together one amino acid at a time. Mechanically guided chemistry has already been achieved, and even automated in some cases, using scanning probe microscopes[3] as well as engineered molecules.[4] Automated manufacture is being developed today, and will be aided by the complete uniformity of atoms. Several branches of nanotechnology are working to develop nanoscale devices.

When precise nanoscale machines are the fundamental components of both the manufacturing system and the product, several important benefits will arise. Certain carefully constructed surfaces can be virtually frictionless and wear-free. Smaller machines operate more rapidly and at higher power density. Flawless structures can be far stronger than today's bulk-manufactured materials, especially when built of carbon—a very versatile atom that is an excellent candidate for molecular manufacturing processes. Systems built of these high-performance machines—including the manufacturing systems—should be many orders of magnitude more powerful than either biological organisms or today's machines.[5]

Strong incentives exist for early and rapid development. The fact that molecular manufacturing can arise from mundane technologies implies that when molecular manufacturing becomes possible, its potential will be extreme by comparison with other contemporary technologies, including the technologies that combine to enable it. As a general-purpose manufacturing technology, it will be applicable in a wide range of contexts, potentially disrupting or replacing a number of industries and activities. Any person or group that has access to molecular manufacturing could out-compete those without access.

- Within a matter of months, and possibly weeks, any nation that possessed a monopoly on nanofactory technology could become the world’s dominant military power.
- Any company that owned the exclusive rights to nanofactory technology would be worth trillions of dollars, no matter how small they started.
- On a less greedy or power-hungry note, any organization that had the awesome potential of nanofactory technology at their disposal could work miracles toward whatever humanitarian or other worthy goals they desired.

Despite the predicted large advantages, it is far from certain that today's centers of innovation and power will develop molecular manufacturing first, or will retain control of it even if they do. In the US, for example, opposition from several prominent scientists has reduced the near-term potential for a nanofactory development program. It may be that by the time a major effort is funded, the resources required will be small enough that multiple independent or competing efforts may be launched by diverse organizations.

A close race to develop nanofactory technology might have unpredictable effects. It could increase proliferation and reduce control. Conversely, it could increase the determination of whoever first achieves a major manufacturing capability to preemptively prevent others from finishing their development projects. In economic competition, this may be as simple as getting patents; in military competition, however, the methods could be far more destructive.

In addition to when it is developed and by whom, a lot depends on how rapidly the technology can be ramped up from the lab to a generally useful manufacturing system. In theory, the transition could be quite rapid. A well-planned program would involve preparatory development of powerful CAD software and early product designs and design skills, so that user-friendly nanofactories and their supporting machinery (e.g. feedstock and power supplies) would be ready to build as soon as the earliest hardware became available. A far-sighted program, in which only debugging would stand between the lab and widespread use, might complete the transition in a matter of months. An incremental program that took development one step at a time—which is the current trend of the US National Nanotechnology Initiative—might easily require years to move from the lab to the user, giving other molecular manufacturing programs a chance to catch up.

NEW PROBLEMS

So far, we have talked about decisions made and problems confronted within the context of the world's major systems of action: Guardian, Commercial, and Informational. But we would be remiss not to mention other issues as well, including environmental implications and new applications of powerful computer technology.

Manufacturing on a massive scale inevitably will have some effects on the environment. These include waste byproducts, such as heat (from running machines) and discarded products. (The manufacturing process itself is not expected to produce waste materials, since every atom will be held in a known position, and can be converted into a useful or at least harmless molecule.) Producing enough energy to supply a rapidly expanding manufacturing economy may also be environmentally problematic—even solar cells require land area.

There are two speculative problems that have been the focus of much controversy and little definitive study. Both involve self-perpetuating systems growing out of bounds destructively. One of these potential problems is mechanical self-replicators that are small enough yet full-featured enough to gather energy and materials from nature. Although such devices—commonly known as ‘grey goo’—would be very difficult to design, and have no economic value, neither the laws of physics nor human nature appear to prevent them from being built. Opinions vary as to how dangerous and destructive such a device could be, and how difficult it might be to clean up. Some experts, including the present authors, tentatively believe that this is not a primary or early risk of molecular manufacturing—unstable arms races appear a lot more serious—but it could be a problem eventually, and certainly merits more study.

The other type of self-perpetuating system is artificial intelligence (AI). This is not a direct consequence of molecular manufacturing, but may be strongly facilitated by it. A number of different scenarios have been proposed by which an AI, designed according to any of several approaches, might successfully usurp most or all resources needed by humans. Serious study and discussion of these issues is just beginning, and should be diligently pursued.

Molecular manufacturing will raise or highlight a number of medical issues. Rapid prototyping of molecule- and cell-scale machine systems should greatly accelerate diagnosis of disease conditions. With good diagnostics, treatment can become more confident and can be developed more rapidly. Within a few years after nanofactory technology arrives in the hands of researchers, most medical problems should be treatable—unless the researchers are hamstrung by obsolete bureaucracy. This raises issues of excessive population, although the growth in resources and efficiency provided by molecular manufacturing should more than compensate for the foreseeable future. (Conversely, denying new and inexpensive medical treatments, or deliberately failing to develop them, would result in many millions of unnecessary deaths.) A more difficult issue is human enhancement. Potentially troubling issues include whether it is ethical to enhance only a subset of humanity, and whether it is ethical (or wise) to enhance people to such an extent that they lose sympathy with unenhanced humans.

A final issue is the increasing integration of computers into human lives, especially in the case of surveillance. Security cameras are becoming a fact of life in public places. However, this is minor compared to the degree of surveillance that could be deployed—and likely will be—once molecular manufacturing makes supercomputers effectively free. It will become possible to monitor and record every volume of human-occupied space, full time, and then search the record with image recognition, object tracking, speech transcription, and data mining. Whoever has access to the surveillance network (or networks) will be able to see into the private lives and actions of anyone they choose. This could create a major shift in human lifestyle, as well as giving unprecedented power to military and law enforcement.

CONCLUSION

Exponential general-purpose molecular manufacturing will create new and extreme opportunities in a number of areas, including personal freedom, concentration of wealth and power, surveillance, widespread abundance, human interactions, and human enhancement. Many of these opportunities will create opposing pressures. Negative consequences, including unstable arms races, massive oppression, and economic upheaval, may spiral out of control. Extreme solutions will act to perpetuate conflict and strengthen the opposing forces. Dealing constructively with these options and competitions will require massive applications of wisdom and creativity.

There may not be much time left to prepare. Already, programmable nanoscale machines have been built, and several different techniques exist for atomically precise fabrication. Several commercially viable technologies are converging toward the atomic scale. Once launched, a well-funded and well-managed development program might require less than a decade to succeed. The amount of funding required will decrease exponentially as time goes on, and may already be under a billion US dollars. The time required may diminish more slowly; thus, delay in starting a program could exponentially increase the potential number of competitors.

It should not be assumed that human nature, presented with an opportunity for unprecedented abundance, will naturally become more constructive. Billion-dollar frauds at a number of large US institutions over the past few years show that even the richest and most powerful people can still be shortsighted and destructive. The governments of Pol

Pot, Idi Amin, and Saddam Hussein further underscore the point that immense power over others frequently will not be used for good. (This should give pause to those who assume that AIs will automatically be benevolent.)

It will not be easy to find a course that minimizes both small-scale human destructiveness—crime, terrorism, and incivility—and large-scale oppression. It will not be easy to give greedy people the capitalist incentive to be productive, while simultaneously preserving the unlimited-sum benefits that can arise from non-scarce unregulated information. Extreme policies will only make things worse—and those who profit from things going wrong may have a strong incentive to promote precisely those policies. The best we can recommend at this point is to increase awareness of the enormous potentials of molecular manufacturing, and then promote intense research into how to avoid the worst problems while maximizing the benefits.

END NOTES

1. *Systems of Survival:A Dialogue on the Moral Foundations of Commerce and Politics* (1992), Jane Jacobs, Vintage

2. For a review of these issues, see "Three Systems of Action" (2003), by Chris Phoenix and Mike Treder, at http://crnano.org/systems.htm

3. See http://www.foresight.org/stage2/mechsynthbib.html for some examples.

4. Nadrian Seeman has built a machine out of molecules of DNA, programmed by other DNA molecules, that assembles DNA strands in programmable sequence. See http://www.trnmag.com/Stories/2005/061505/DNA_machine_links_molecules_061505.html

5. For more information, see http://e-drexler.com