6.4 FOCUS ON MEDICAL, ENVIRONMENTAL, SPACE EXPLORATION AND NATIONAL SECURITY IMPLICATIONS

CHALLENGES AND VISION FOR NANOSCIENCE AND NANOTECHNOLOGY IN MEDICINE: CANCER AS A MODEL

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The recognition of the molecular basis of cancers creates the opportunity for a future where cancers are detected, diagnosed, and treated based on the fundamental changes in the specific disease. Ongoing efforts target the definition of the genes and expressed gene products of the human genome, the discovery of sentinel biomarkers of the early presence of disease, and establishment of informative diagnostic classification systems based on the fundamental molecular changes. Closely linked are efforts to discover and exploit molecular targets for cancer prevention and treatment. New technologies are needed to speed the discovery process that are rapid, highly parallel, and cost-effective. Reductions in the scale of analysis tools and automation are proving critical to enabling the discovery of the fundamental changes associated with the development of cancers, and insight into the molecular processes of the cell.

The identification of molecular signatures of cancers will enhance our ability to identify and accurately diagnose disease. Our goal is to use this information to identify cancers or precancers at the earliest point in the disease process and intervene before symptomatic disease becomes apparent. Realization of this goal will only be possible if technologies exist that allow us to scan the living body for the earliest signatures of emerging disease and support immediate, specific intervention. The ability to scan the body for early signatures requires these technologies to be minimally invasive. The ability to scan the body for molecular signatures will also allow us to monitor the progress of disease and effects of interventions.

The NCI is currently seeking technologies that will support the earliest detection of the molecular signatures of cancer and serve as a platform for the seamless interface between detection, diagnosis, and intervention. Platform technologies must integrate the ability to sense, signal, respond, and monitor. Nanotechnologies are emerging as enabling components to these goals. Ongoing efforts highlight that full systems will require the integration of new discoveries from a variety of fields including nanoscience, chemistry, photonics, computational sciences, and information science and technology.

NANOTECHNOLOGY IN MEDICINE

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Nanotechnology, which can be presently viewed as the promise of a technology, could have a profound impact in medicine in the not too distant future. But incorporating now nanoscience in the national research agenda for advanced medicine is important not only for the obvious reason but also because this enormous challenge will impact science broadly, and help us make the needed cultural transition to interdisciplinarity. Nanotechnology in medicine is about the hybridization of physical sciences, biology, engineering, and clinical medicine. It is difficult to identify an area that requires this much synergistic mixing of traditional fields. This fact poses an educational challenge at all levels.

The promise of nanoscience for medicine rests on various grand challenges. An important one is connected to our abilities to manipulate the behavior of a “single cell” or groups of cells of common phenotype using synthetic nano-objects that are targeted to interact specifically with the cell’s own functional nano-objects (i.e., receptors, cytoskeleton parts, specific organelle locations, nuclear compartments, etc.). Into the future this area will allow us to diagnose disease at much earlier stages than we do presently, reverse disease, repair or re-grow human tissues, maybe enhance human performance when needed (this of course touches on complex dilemmas for society not commonly addressed by scientists).

Among other things, the challenge is related to what chemistry does not yet do well at all, teach the synthesis of well-defined objects in the 1-100 nanometer range. This will require also understanding and inventing new modes of molecular recognition, new tools to manipulate and detect the presence of exceedingly small numbers of nano-objects such as proteins inside and outside of cells. Engineers and physicists will play key roles in the development of these tools, but of course the users, clinicians, will have to guide and help prototype nanotechnologies in medicine. Finally, it is clear that advances in nanoscience for medicine will impact in parallel other fields such as environmental detection of toxins and pathogens and maybe our abilities to manipulate agriculture at a level not yet experienced.

LIFECYCLE/SUSTAINABILITY IMPLICATIONS OF NANOTECHNOLOGY

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Abstract

Nanotechnology has the potential to be the new technological wave that increases environmental quality and sustainability. By reducing the amount of energy and materials required to accomplish a desired task, nanotechnologies can provide the goods and services we desire “smarter, cheaper, faster” and with a smaller environmental footprint. Transistors and later microprocessors are part of the evolution of accomplishing our consumption goals with less energy and materials. A standard graph shows the rapid decline in the cost of memory or logic. The graph might be reconfigured to show the decline in the amount of energy, materials, or environmental discharges required to perform a calculation or store a byte. Nanotechnology may be the next step. It promises to reduce by orders of magnitudes the inputs of energy and materials and associated environmental discharges required to produce a device that can perform a particular task. The result could be perhaps an order of magnitude increase in real income for the current world population without requiring more energy, materials, or

resulting in additional discharges. Thus, nanotechnology offers the prospect of giving poor nations much higher standards of living and making the world economy sustainable.

In biological systems, the population of a species will continue to grow as long as there is food and other conditions that permit growth. No individual, or the species, evidences concern that the population might be growing too large to be sustainable. Often, the expansion results in over-population and a crash with many individuals starving.

A widely read book of the mid 1970s, *Limits to Growth*, assumed the same behavior would occur for human populations. It assumed that the population and use of energy and materials would continue to grow exponentially. Meadows et al. (1972) found that, eventually, there would be a catastrophic crash, as fossil fuels and raw materials were exhausted. The book demonstrated the truth that exponential growth is inconsistent with a finite world.

Two centuries ago, Thomas Malthus explored the same notions, concluding that humans would continue to breed until starvation, pestilence, and war limited the population size.

Income in England is far greater than in Malthus' time. While there is starvation, this seems to have more to do with conflict than any inherent shortage of food (Simon 1995). Life expectancy has increased in all the developed nations and in almost every part of the world. Thus, aside from human conflict and a relatively small burden of disease and natural disasters, people live much better than Malthus predicted.

Malthus and Meadows et al. (1972) erred by not accounting for the effects of technological change, with its inherent ability to substitute abundant materials for scarce ones. They also erred by not accounting for the feedback in a market economy. Scarcity causes increasing prices, which signal inventors to find substitutes, prospectors to find other supplies, and consumers to use less or find substitutes.

Humans are different from other animals in explicitly and implicitly accounting for the systems wide impacts of their actions, including having more children. Even when consumers don't think about the economy-wide effects of increased population, a market will react to increasing population by increasing the price of scarce food and other materials and by lowering family income (by decreasing the wage rate, or increasing unemployment). Both effects lower the standard of living and cause people, eventually, to think about the desirability of having so many children. The feedback effect can take decades and the signals often are misinterpreted, but the market signals get stronger as population outpaces the ability to support the population. Thus, humans are fundamentally different from bacteria, plants, and other animals. We have institutional feedback systems that prompt people to reassess their decisions to have more children before there is a disaster.

The importance of technological change cannot be overstated. Humans started out as foragers, dependent on the bounty of nature. To support a growing population and to ensure a steady food supply, humans developed agriculture. Agricultural techniques developed over time, including breeding more productive plants and animals, irrigation, mechanization, and the use of fertilizers and pesticides.

Wood was a primary energy source for cooking and smelting metals. As the forests of Europe were depleted, people hunted for, and eventually found a substitute in coal, and later in petroleum and natural gas. Mining coal, transporting it, using it to reduce iron ore, and learning to burn it without excessive pollution required vast improvements in technology. Finding and producing petroleum and natural gas posed still greater challenges to technology.

Rich deposits of ores for tin, copper, lead, and iron were gradually exhausted in Europe (Tilton 1991). Technology developed to produce the metals from less rich ores and to find substitutes. Iron ore is more plentiful than ores for tin, lead, and copper (used to make bronze). Tin cans for storing food compete with glass jars. The competition among materials led to recycling as well as thinning the layer of tin in order to lower cost. Technology was called upon to use expensive resources more productively and to find substitutes. Similarly, the scarcity of natural rubber during World War I led to the development of synthetic rubber, made from petroleum. Petroleum shortages in Germany during this war led to the development of synthetic fuels made from coal.

How Many People Can the Earth Support?

People such as Ehrlich (1977) have been deeply concerned about over-population and the ability of the Earth to feed increasingly large populations. The Earth currently supports 6 billion people. As noted above, aside from political problems, wars, and occasional natural disasters, the 6 billion people have enough to eat and many are far above subsistence level. This is not saying that the quality of life is high for all 6 billion people, since there would be less crowding with fewer people.

It seems self-evident that the Earth could not support 6 billion people if they were all foragers. There are not enough roots and berries and game to support so many people. If foraging were the technology for feeding people, most would starve.

Similarly, if the technology were early agriculture with its primitive grains, lack of pesticides, fertilizers, and irrigation, most people would starve. There simply is not enough good farmland to support so many people without the improvements that have come from plant breeding, pesticides, fertilizer, and irrigation.

The standard of living in the United States is far above subsistence because only about 2% of the workforce is required to produce the food. Particularly in the last century, the combination of technological change and clever use of resources has outpaced population growth, especially in the developed nations. However, current agriculture, and the economy more generally is built on a foundation of fossil fuels, underground aquifers, and other resources that are very finite. If current technology were used to provide all 6 billion people with American lifestyles, we would quickly exhaust petroleum resources, ores, water supplies, and pollute the environment. Can technological change and clever resource use continue to outpace population growth? Will world population growth slow and then be transformed into decreasing world population? I am optimistic, but the world of 2100 is unknowable.

Nanotechnology Opportunities

Burning fossil fuels is the primary source of pollution, including polluted air and greenhouse gas emissions in the USA. Nanotechnology offers the promise of being the foundation for the next wave of technological change. The energy from fossil fuels is used extremely inefficiently. Nanotechnology could provide improved services for a small fraction of current energy in lighting, computing, printing, water filtration, and many other areas. For example, only a few percent of the energy in gasoline is actually used to get me where I want to go. The current internal combustion engine is about 15% efficient in transforming the energy in the gasoline into power to turn the tires. In addition, the average car weights about 3,000 pounds and is transporting one 160-pound person. There is no reason in principle why converting the energy in gasoline into useful work could not be five times more efficient. Similarly, there is no reason in principle why the amount of non-useful material transported with me could not be reduced by a factor of ten. If so, person transportation vehicles could be 50 times more efficient than at present.

The Dark Side of Nanotechnology

Every intervention in natural systems has undesired consequences. For example, the historian Lynn White (1974) asserts that the cause of the French Revolution was the invention of chimneys. Prior to chimneys, every member of the household slept around a fire in a room with a hole in the roof. The invention of chimneys permitted individual rooms to be heated and vented, allowing the rich to distance themselves from their servants and the poor, eventually leading to the excesses of Louis XIV and the French Revolution.

In a far more direct way, new technology has undesired consequences that can nullify its advantages or at least require considerable changes. For example, asbestos is a marvelous insulator and wonderful at fireproofing. However, the small fibers cause asbestosis, lung cancer, and mesothelioma. Despite its wonderful properties, asbestos has been banned in the USA.

To assess a nanotechnology, a lifecycle analysis is needed. Are there hazardous materials produced? Do parts of the product cause safety hazards? Are the needed materials in abundant supply?

The Green Design Initiative has evaluated some technologies that are well thought of, or even required by regulators. The conclusions can be surprising. For example, the California Air Resources Board initially required that 2% of new cars sold in 1998 had to be zero emissions vehicles. The only vehicles that satisfy the requirement are battery-powered vehicles. Lave et al. (1995b, 1996), found that mining and smelting the lead and then making and recycling the 500 kg battery in an EV-1 would result in 4-60 times as much lead being discharged into the environment, per vehicle mile, as a comparable car using leaded gasoline. Similarly, large amounts of nickel and other heavy metals would be discharged into the environment if the batteries were made from nickel metal hydride. Another evaluation found that, while hybrid-electric cars are more fuel efficient and less polluting than cars using a conventional internal combustion engine, the differences are small and not commensurate with the increased production cost (Lave and MacLean, 2000). While it advances technology, the Toyota Prius hybrid electric vehicle is not cost-effective.

The Potential for Nanotechnology

One idea of the potential for nanotechnology can be seen in Table 6.1. This table uses our lifecycle software (Lave et al. 1995a; Hendrickson et al. 1998) to compute the resource use and environmental discharges of several sectors. (This software was developed, in part, with NSF funding and is available free on the web at www.eiolca.net.)

The table lists the amount of materials, energy and environmental discharges associated with purchasing $1 million worth of that output. The first column lists the categories that we tabulate for each sector. These include total energy, various fuels, ores, water, and various categories of environmental discharges. The second column is the electricity generation sector of the United States. This sector uses a great deal of coal, natural gas, petroleum, nuclear and hydropower, and small amounts of renewable technologies, such as wind power. Since it uses such large amounts of fossil fuels, it generated a great deal of environmental discharges, particularly into the air.

Table 6.1. Life Cycle Implications of $1 million Sale by Sector

Effects	Electricity	Steel	Aluminum	Computers	Computer Services
Electricity Used [Mkw-hr] x 10	1	19	138	3	1
Energy Used [TJ]	147	74	54	7	3
Conventional Pollutants Released [metric tons]	105	52	106	5	3
OSHA Safety [fatalities]x10,000	7	9	7	4	3
Greenhouse Gases Released [metric tons CO_2 equivalents]	12570	6140	3002	460	226
Fuels Used [metric tons]	4997	2443	1165	175	85
Ores Used [metric tons]	28	370	323	172	35
Hazardous Waste Generated [RCRA, metric tons]	15	75	76	32	10
External Costs Incurred: as Percentage of Revenue	34	14	15	1	1
Toxic Releases and Transfers [metric tons]x10	2	72	27	9	2
Water Used [million gallons]	1	66	18	2	1

The total amount of energy used to generate $1 million of electricity is 147 terajoules. The electricity sector purchases 0.1-megawatt hour of electricity. It releases 105 metric tons of conventional air pollutants and 12,570 metric tons of greenhouse gases (carbon dioxide equivalent). Producing the electricity results in 7/10,000 of a fatality. Generation uses 4,997 metric tons of fuel and 28 metric tons of ores (to produce the steel, etc. for the plant). Generation results in 15 metric tons of RCRA hazardous waste and 2 tons of toxic releases and transfers. The external cost of releasing the air pollutants is 33.9% of the total revenue or $339,000. Finally, generation uses 1 million gallons of water.

Clearly, conserving electricity would be worth a great deal toward sustainability and environmental quality.

The next two columns show the implications of purchasing $1 million of steel or aluminum. Aluminum uses much more electricity than steel, but steel uses more total energy (twice as many tons) and so releases more greenhouse gases. The sectors are similar in terms of ores used, hazardous wastes, and external costs. However, steel results in more toxic releases and transfers and water use. Because it uses so much electricity, aluminum is responsible for twice the emissions of air pollutants. The industries are comparable in terms of work related fatalities.

Column 5 shows the implications of buying $1 million worth of electronic computers. This sector is much more benign than the previous three sectors.

The final column shows the implications of buying $1 million of computer and electronic data processing services. This sector is still more benign than producing computers, since it performs a service rather than making a product.

For the computer sector, about 20% of the energy and materials use and of the environmental discharges are due to the sector directly, while all the rest is due to industry suppliers. For computer services, only about 4% is due to the sector itself, with 96% due to suppliers. Thus, if both sectors could use less electricity and steel and aluminum, their environmental footprint would be appropriately smaller. In particular, if nanotechnology enabled electricity to be generated with less fuel and less environmental discharges, that would make a huge contribution to decreasing the environmental footprint of this sector. Similarly, if computers could be made with less energy and raw materials, it and computer services would be enormously benefited.

These lifecycle calculations demonstrate the potential benefits for improving environmental quality and sustainability. Nanotechnology could make a large contribution to lower resource use and environmental discharges.

Comment in Plenary Discussion

The general public has become increasingly concerned about the safety and environmental implications of new technologies, from nuclear power to chemicals to biotechnology. Statutes such as the Toxic Substances Control Act and Food, Drug, and Cosmetic Act require government review of new chemicals and other technologies before they can be sold. Although proponents of nanotechnology view it as benign, there are likely to be some unforeseen, undesirable effects.

Even at the basic research stage, nanotechnology advocates need to inform the public about the prospects and risks. They need to engage and involve the public and the groups that represent them. While this will delay the introduction of new technologies, in the end it is likely to save time.

To win support for this initiative from Congress and the general public, nanotechnology advocates need to specify the social problems that can be addressed by nanotechnology. They need to make a convincing case that expenditures will be more productive in addressing these problems than would be expenditures on a variety of other social programs, from paying down the debt to tax cuts to Medicare prescription benefits.

In communicating with Congress and the general public, it is important to use their language and to make the communication understandable.

The social sciences have much to offer in addressing issues of evaluation, communication, and addressing social needs.

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IMPLICATIONS OF NANOTECHNOLOGY FOR SPACE EXPLORATION

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Abstract

Typically when NASA begins a new technology program the Agency is most concerned about the performance benefits, cost of development, time for development and new opportunities that are enabled. Ethics becomes part of the process if the development or ultimate use of the technology directly affects the health or well being of humans or other living creatures. However, as we move into the era of nanotechnology we are also encompassing biology and fundamental biological processes. Our vision of nanotechnology encompasses the attributes of self-generation, reproduction, self-assembly, self-repair and natural adaptation. These are all attributes we ascribe to living things. Thus, we are moving beyond the typical bounds of technology into the domain of natural philosophy. This can have significant implications for the public attitude toward such technology.

Nanotechnology will enable NASA to build future systems with many of these "life-like" characteristics. We need this capability for our robotic systems to operate at great distances from Earth, in harsh environments without the benefit and high cost of continuous human control. As we develop new nanotechnology we must also pro-actively establish policies and guidelines to assure the technology and systems made from it are socially acceptable to the general public.

Ethics as a Decision Criteria for Technology Planning and Development

During the early days of the Space Age, the United States was forced to develop spacecraft that were small but powerful. We lacked the large launch vehicles that could put heavy payloads into orbit so we concentrated on developing miniature systems. The microelectronics revolution was a product of this era. However, by the 1970s the spacecraft NASA was building for deep space missions had grown to weigh thousands of kilograms. This trend continued into the early, 1990s. Viking, Galileo, Voyager, Magellan and Cassini all weighed thousands of kilograms at launch. These missions also cost billions of dollars. Though much of this weight was in propellant, the total spacecraft weight was driven by the size of the final payload.

In the early 1990s NASA moved away from large expensive missions and focused on developing spacecraft an order of magnitude smaller and less expensive. In addition, NASA increased its efforts to develop on-board "intelligence" to reduce the cost of operations. For some of NASA's missions, the cost of maintaining an "army" of operators to monitor and control every critical function of the spacecraft was comparable to the cost of the spacecraft itself.

This move toward smaller, smarter, lower cost systems has become essential if the Agency is to accomplish its future missions. As we look to the future, all of the "easy" missions have been accomplished. We have flown by every planet except Pluto and orbited Venus, Mars and Jupiter. Cassini will eventually orbit Saturn. The only planetary body we have explored in person is the moon — and even that for less than three weeks in total. Space exploration of the future will be characterized by more in-depth investigations. We will put spacecraft on the surface of planets, moons, asteroids and comets. We will explore below the surface and in the atmosphere as well. Closer to home we will explore the structure and dynamic behavior of the Earth's geomagnetic environment and distribute spacecraft in strategic locations to learn about the intimate relationship between the Earth and the sun.

One of our highest priorities is to search for life elsewhere in the solar system. While space exploration of the past may have excited the country, the future looks even more exciting. We have recent evidence of liquid water near the surface of Mars and there is the real possibility of more water below the icy surface of Europa than in all the oceans on Earth. And, on Earth everywhere we have found water we have also found life, so these recent discoveries are all the more exciting. While our initial "explorers" will be robots, if our solar system proves a sufficiently vibrant source of scientific discovery human explorers will eventually follow.

However, our current challenge is to develop space systems that can accomplish our missions effectively and economically. To do this they will have to be much more capable than today's spacecraft. They will have to have the characteristics of autonomy to "think for themselves"; self-reliance to identify, diagnose and correct internal problems and failures; self repair to overcome damage; adaptability to function and explore in new and unknown environments; and extreme efficiency to operate with very limited resources. These are typically characteristics of biological systems, but they will also be the characteristics of future space systems. A key to developing such spacecraft is nanotechnology.

We are already seeing the potential of nanotechnology through the extensive research into the production and use of carbon nanotubes, nano-phase materials and molecular electronics. For example, on the basis of computer simulations, and available experimental data, some specific forms of carbon nanotubes appear to possess extraordinary properties: Young's modulus over one Tera Pascal (five times that of steel) and tensile strength approaching 100 Giga Pascal (over 100 times the strength of steel). Recent NASA studies indicate that polymer composite materials made from carbon nanotubes could reduce the weight of launch vehicle — as well as aircraft — by half. Similarly, nanometer-scale carbon wires have 100,000 times better current carrying capacity than copper, which makes them particularly useful for performing functions in molecular electronic circuitry, now performed by semiconductor devices in electronic circuits. Electronic devices constructed from molecules (nanometer-scale wires) will be hundreds of times smaller than their semiconductor-based counterparts. However, the full potential of nanotechnology for the systems NASA needs is in its association with biology.

Nanotechnology will enable us to take the notion of "small but powerful" to its extreme limits. Biology will provide many of the paradigms and processes for doing so. Biology has inherent characteristics to enable us to build the systems we need: selectivity and sensitivity at a scale of a few atoms; the ability of single units to massively reproduce with near zero error rates; organization capability to self assemble into highly complex systems; the ability to adapt form and function to changing conditions; the ability to detect damage and self repair; and the ability to communicate among themselves. Biologically inspired sensors will be sensitive to a single photon. Data storage based on DNA will be a trillion times more dense than current media; and supercomputers computers modeled after the brain will use as little as a billionth the power of existing designs. Biological concepts and nanotechnology will enable us to create both the "brains and the body" of future systems with the characteristics we need. Together, nanotechnology, biology and information technology form a powerful and intimate scientific and technological triad.

An example is intelligent multifunctional material systems consisting of a number of layers, each used for a different purpose. The outer layer would be selected to be tough and durable to withstand the harsh space environment, with an embedded network of sensors, electrical carriers and actuators to measure temperature, pressure and radiation and trigger a response whenever needed. The network would be intelligent. It would automatically reconfigure itself to bypass damaged components and compensate for any loss of capability. The next layer could be an electrostrictive or piezoelectric membrane that works like muscle tissue with a network of nerves to stimulate the appropriate strands and provide power to them. The base layer might be made of bio-molecular material that senses penetrations and tears and flows into any gaps. It would trigger a reaction in the damaged layers and initiate a self-healing process.

Such systems will use the design and fabrication methods very different from those we use today. Today, we build most of our systems by starting with volumes of material and "chipping" away what we do not need, or by selectively layering material over "large areas" — large compared to the scale of the phenomenon we are trying to control. Doing so, we can produce several million transistors on a single microchip. But we are still limited by our ability to cut or to layer. By contrast, biology intrinsically works at the atomic level and builds systems far more complex than anything we can build today, atom by atom. Such nanoscale systems can be 10,000 times smaller than current systems.

This same technology will also enable us to send humans into space with greater degrees of safety. While the vehicle they travel in will have much greater capability — and display the same self-protective characteristics of spacecraft — nanotechnology will enable new types of human health monitoring systems and health care delivery systems. Nanoscale, biocompatible sensors can be distributed throughout the body to provide detailed information of the health of astronauts at the cellular level. They will have the ability to be queried by external monitoring systems or be self-stimulated to send a signal, most likely through a chemical messenger. NASA is currently working with National Cancer Institute to conduct research along these specific lines.

The societal implications will not just be new and exciting space exploration missions. As in the past, the demands of space exploration have resulted in scientific and technological advances with great benefit to the country in general. The communication satellites we depend on so heavily today are products of the country's space program. The monitoring systems used in intensive care units and in heart rehabilitation wards are descendants of the systems used to monitor the heart beat of astronauts during the first space missions in the early 60s. Today we take such technology for granted.

Recently scientists have found tiny biological motors naturally occurring within cells. Their biological function is to help the cell generate energy, but they are also amazing little machines. They look like a tiny ring of footballs with a broomstick in the middle. Each of the components is a large complex molecule. In the process of generating energy for the cell the “shaft” in the center of the “motor” spins, like a microscopic electric motor.

NASA is supporting research to employ these biomolecular motors as the power source for fabricated nanomechanical devices. These devices are fueled by the chemical sources that provide energy to the cells and thus can potentially be safely and seamlessly integrated with a living host. One of the potential uses for these devices is to create cellular pharmacies that could dispense medication directly into individual cells. They would be coupled to nanosensors that would detect when medication is needed and dispense exactly the right amount molecule by molecule. Because the biomolecular motors are fabricated using the machinery of life, there exists the very real possibility that we will be able to develop devices that are self-assembling and self-repairing.

The current era of nanotechnology is still in an embryonic stage and its full potential can only be speculated. But, combined with biology and information technology it can lead the way to a technical revolution as significant as Newton’s laws of gravity and motion, electromagnetic theory of the 1800s or atomic theory, relativity and genetic discoveries of the past century.

However, a distinct difference is that as we merge nanotechnology with biology and information technology we will be building systems that become more and more “life-like” and which interact with and support living systems at the cellular level. On the positive side this will result in systems that more effectively meet our needs and communicate with us on our own level — for example, natural language. Sensory systems such as sight, sound and touch will mimic our own, though exceed human performance levels. This is what we envision for space systems.

But, there is a “down side” as well. As we proceed along this path we must be sensitive to the perception that our “life-like” technology and systems are actually “living” systems and that systems which are designed to interact with humans in a “human-like” manner may viewed as being “too human”. In the past this has been the domain of science fiction; in the foreseeable future it could be reality. Our view at NASA is to be pro-active in developing ethical standards to make clear that we understand the accepted boundaries between true “life science” and “life-like” science. And, to make sure that our use of biological analogs and processes remains in the domain of technology. This will require us to engage others outside the fields of science and technology that NASA is most familiar with. It will not be sufficient to have approval of social and ethical leaders. We will have to maintain the acceptance of the general public. Currently, NASA has initiated a process to establish a task force under the NASA Advisory Council to specifically address ethics and technology.

NASA’s role is explore the boundaries of aeronautics and space with machine and with people. As we do so the safety of our people is the highest priority, followed by the overall success of our missions. We will always use robotic systems wherever possible, and always when the safety of an astronaut cannot be adequately assured. Nanotechnology will provide the capability to build the small, compact systems that can perform tasks that today only humans can perform, and to do so economically and efficiently.

Nanotechnology holds great promise of revolutionizing space exploration with the effect of developing technology of great benefit to us on Earth. But, as we fully realize this potential we must proceed carefully.

NATIONAL SECURITY ASPECTS OF NANOTECHNOLOGY

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Abstract

Nanotechnology represents a wide spectrum of disciplinary and interdisciplinary research frontiers that will have a positive technological impact influencing our social and economic well being. National security, both economic and military, represents one vital aspect of governmental concerns that will be impacted by the anticipated discoveries and developments in this field. Competition for economic security represents an important aspect of nanotechnology while augmenting military security and defense capabilities. The development of nanotechnology offers much enhanced capabilities to the Department of Defense (DOD) in the performance of its mission. On the other hand, even though nanotechnology is at an embryonic stage in its development, "visionaries" have imagined powerful and, in some cases, frightening capabilities emerging from this technology. Many of these imagined capabilities are irrational, generated from hypotheses far removed from experiments and the laws of nature as we understand them today. Without any scientific bases, dire predictions of self-replicating species cause fear in the society that is already facing a threat from biological agents similar to that from other hypothetical self-replicating entities. Such fears are generated for a technology whose ultimate capabilities are not well understood at present. Many irrational fictional predictions represent a potential barrier to progress by raising imagined and very unlikely scenarios. A series of experiments and/or observations is proposed that should serve to alert the scientific community, and society in general, to take action when progress approaches the possibility that it poses a threat to society.

Introduction

National security involves the protection of our form of government and our way of life from internal and/or external threats, and involves maintaining stability in national and international functions such that violent force (or a threat of force) is not used to influence economic and social discourse. This involves not only open warfare, but includes localized conflict, terrorism, and a wide variety of combat scenarios as well as missions in peacekeeping. Maintaining a strong defense has been a key component of national security in the U.S. A keystone of U.S. defense posture includes maintaining a strong Science and Technology R&D program in order to have leading edge technologies available for timely weapons development as required. Nanotechnology represents one of these emerging technologies that can provide much needed enhanced capabilities to DOD.

The International Nature of Nanotechnology

To view nanotechnology in the proper perspective relative to national security, it is necessary to understand that research in nanotechnology is without national borders. As such, nanotechnology is an exciting research frontier pursued by many nations for more than a decade. Europe and Asia are strong competitors with the U.S. for advances in nanotechnology. As one way to gauge the level of efforts in other countries, the number of recent papers mentioning the word "nano" in their title in five regions of the world is given in Table 6.2. Although different nations may use the phrase "nano" in different contexts, with some deference to wording introduced by translation, it seems clear that the U.S. is second to Europe in activity involving nanotechnology. Further, Asia has a substantial effort rivaling that in Europe. The U.S. must compete with other nations in this hotly contested field of nanotechnology.

Table 6.2. Number of Open Literature Articles, 1999-July 24, 2000[1]

Country	No. Articles on Nano	No. Articles In Database
China	1,120	41,175
Europe	3,309	550,427
Japan	1,121	124,195
Russia	472	44,644
USA	2,321	170,367

To a significant extent, economic security impacts on the security of a nation. Rapid declines in industrial competitiveness can lead to large levels of unemployment, unrest, and a basis for security issues. It is vitally important to maintain a competitive edge involving enterprises considered important for international competitiveness. The pervasive nature of nanotechnology research, and the important anticipated products that will influence future industrial products, implies the need for vigorous research programs to pursue the opportunities offered in this emerging technology.

[1] Articles available in the Science Citation Index database were searched for these statistics. A more detailed examination was made involving 200 papers from each of five regions: China, Europe, Japan, Russia and the USA. The most recent papers from these regions that were documented by Science Citation Index during 1999-July 24, 2000 were chosen to obtain a statistical sample. Titles were examined that contained the word "nano-;" in almost all cases, about 90%of these titles represented efforts in nanotechnology as we consider it in the U.S. (excluding efforts with the word "nanoseconds," for example).

Contributions to National Defense

Nanotechnology is an appropriate term encompassing many research disciplines actively pursuing scientific frontiers involving matter at nanometer dimensions. The development of proximal probes (including the scanning tunneling microscope, atomic force microscope, and many derivative instruments) and other tools to examine the properties of matter at these dimensions have brought together several disciplines anxious to use these tools to advance the more traditional pursuits. Understanding and manipulation of materials at the atomic and nanometer scale has reached unprecedented capabilities in these disciplines. Contributions of nanotechnology to traditional defense systems will be many. It takes little imagination to elucidate developments that will lead to advanced materials, sensing and signal processing, information technology, battle management, casualty care, or medical procedures and medicines. These science and engineering fields will advance through the use of tools and new knowledge uncovered by research in nanotechnology. Additional benefits in other fields will also occur. Many excellent discussions involving the prospects of nanotechnology need not be repeated here (Roco 2000).

Advances in nanotechnology in the civilian sector will provide advantages to national security and military capabilities through "commercial off-the-shelf" systems ("COTS") as well as through technologies and systems developed by defense laboratories. In many cases economic and military opportunities are considered to be complementary. This is a reflection of the basic theme by Paul Kennedy in his book, *The Rise and Fall of the Great Powers* (Kennedy 1987). After tracing the history of many nations, Kennedy reached the conclusion that a major consideration affecting the sustainability of nations was the need to keep national economic and military levels of effort in balance. This lesson must be remembered and remain a guiding light for the influence of nanotechnology on national security.

The traditional opportunities anticipated from research in nanotechnology (Roco 2000) may be rearranged in an alternative taxonomy to view the subject from a military perspective. At the present stage of discovery and development, these opportunities represent evolutionary improvements in military technology rather than any dramatically different approach. Many revolutionary capabilities are yet to be uncovered. Certainly, as we develop and implement many of the anticipated enhancements to traditional military defense, we must be aware that any potential adversaries have an equal opportunity for introducing such advantages. The competitive process involving technological superiority as it is applied to warfare has continued for centuries.

A preliminary list of these opportunities using terms and objectives more in line with a DOD posture includes the following:

1. Higher performance platforms (aircraft, ships, subs, boats and satellites) through stronger, lighter weight structural materials, stealth materials, and low maintenance and "smart" materials.

2. Enhanced sensing through more sensitive and selective sensors of electromagnetic radiation, magnetic and electric fields, nuclear radiation, and chemical/biological

agents. Miniature systems capable of mobility and highly sensitive/selective sensors, combined with wireless communication, are envisioned for remotely determining the state of a potential battlefield.

3. Enhanced human performance through improved monitoring devices, even through an introduction of appropriate biological materials to enhance performance. Devices of all kinds to sense the state of a war fighter's physiological condition will enhance his/her effectiveness.

4. Information dominance through enhanced information technology. This is likely to take the form of smaller, lower power memories, smaller and faster logic devices through improved processing, and enhanced secure communication systems with greater bandwidth.

5. Safer operation involving hazardous materials or operations, through the use of remotely operated robots.

6. Reduced manpower requirements through the greater use of automation in the maintenance, management and control of weapon platforms, systems, and hazardous functions.

7. Improved battlefield casualty care through the use of materials and procedures; for example: artificial blood substitutes, burn treatments, and biocompatible materials.

8. Battlefield remediation of chemically or biologically contaminated areas and/or equipment through the use of enhanced chemicals and procedures.

9. Lower life-cycle costs through the use of improved materials, coatings, and condition-based maintenance.

An active nanotechnology program involving researchers in the Department of Defense, spanning the activities in academia, industry, and defense, is necessary. It is by such programs that the necessary scientific knowledge and understanding is gained and transferred in an optimum manner. This breadth of R&D activity provides an efficient mechanism for military applications.

The Emergence of Irrational Visions

The question involving developments in nanotechnology, and whether they (along with sister research areas of genetics and robotics) represent destabilizing national security has become of increasing interest this year (Joy 2000). Visions of "smart" self-replicating miniature robotic systems easily manufactured by a rogue state (or terrorist group) have received considerable attention. "Visionaries" who have never performed experiments have nevertheless constructed scenarios raising highly questionable possibilities. Due to a lack of contact with reality, they envision a world in which ideal "machines" assemble atomically perfect systems having surprisingly "smart" capabilities. These systems are ostensibly not only capable of reproducing themselves, but are intelligent, and may be constructed to cause harm to the environment or living species. There seems little doubt that such systems are figments of imagination by very creative minds, and are nearly impossible based on the laws of physics, thermodynamics, or other laws of nature, as we understand them. Predictions of such occurrences, however, have caused so much concern that addressing the subject rationally is appropriate.

Many statements have appeared representing bizarre predictions resulting from uncontrolled progress in nanotechnology. The following is one such example:

> The possible applications of nanotechnology to advanced weaponry are fertile ground for fantasy. It is obvious that three-dimensional assembly of nanostructures in bulk can yield much better versions of most conventional (non-nuclear) weapons; e.g., guns can be lighter, carry more ammunition, fire self-guided bullets, incorporate multispectral gun sights or even fire themselves when an enemy is detected. Science fiction writers can and do have a lot of fun imagining such things. (Gubrud 1997)

"Fertile grounds for fantasy" represent much of the hype surrounding nanotechnology today. Most such statements belong in the realm of science fiction. Discussions have included the concept of weapons that "fire themselves" when an enemy is detected. To the knowledge of this author, under all circumstances, decisions in the U.S. have avoided consideration of any such weapons; a decision to take a life is not left to a mechanical device, even a "smart" one involving the processing capability of a computer.

Another paragraph, representative of the profuse appearance of hype in the community, is:

> With nanotechnology, you can build a machine the complexity of a fighter jet the size of a gnat. If the aliens put just a few percent of the mass of machinery they are shown as having, in the form of military gnats, the humans are sunk. The gnats can be everywhere, not just one per city. What's more, the humans have nothing to shoot back at. They can protect themselves with hermetically sealed suits and buildings, but how many of us have those? The gnats simply fly up to you, inject a few micrograms of botulin toxin or the equivalent, and you become very extremely dead. (Storrs 1996)

Public perceptions are formed by press releases and interviews, which have echoed many irrational thoughts about this subject without any scientific validation. Today, exchanges on the Internet are beginning to have nearly as big an impact as other media. Viewing the subject of nanotechnology on the Internet today reveals a vast medium of hype and misperceptions. Any program associated with nanotechnology must be concerned about the implications of a surge of interest by young, impressionable students (mature adults are also included!) influenced by such distorted views.

Terrorism

Will the activities of nanotechnology be used in the future to add to the repertoire of terrorist activities? Can dangerous species be created willfully or by accident? Could research in this field provide a means of placing dangerous weapons in the hands of irresponsible individuals? Bill Joy, co-founder of Sun Microsystems, addresses this question in his initial article (Joy 2000). It is this point that is found to create the most concern by the many newspaper articles that followed his article. Consider the exchange appearing in the London Times:

> Q (by the interviewer): Is it a question of whether we should do something rather than whether we can do something?
>
> A (by Bill Joy): It's clear there are some things we shouldn't do. Genetically engineered viruses for example shouldn't be touched. But people can now give each other bioengineering equipment for Christmas. Clinton and Blair are trying to make technology available to everyone without first thinking about whether those people understand its uses. If we continue the way we're going, without thinking about the consequences, the technology will be misused. This technology can be used for genocide. You can't just sit by even when this word is hinted at. .....
>
> I don't think rogue corporations are a likelihood, it is much more likely to be smaller groups. Look at Monsanto; they were stopped without even losing a lawsuit. If corporations became more powerful then maybe... but the dangers I think are much more likely to come from terrorism and individual craziness.

This exchange suggests the greatest concern by the lay public relates to the ability of an individual or small group to knowingly or unknowingly create a species (in this case, biological in nature) that may introduce a menace in the form of a harmful virus or self-replicating entity unleashed in the environment (or society). Such attempts have been documented in Japan (Drell 1999).

Self-Replication

"Autonomous, self-reproducing machines are a computer-science quest that dates back to John von Neumann in the 1940s" (Storrs 1996). Artificial life is a subject of active investigation today (Di Paolo 2000; Lipson2000). It is safe to say that many variations in the DNA structure of viruses and bacteria have appeared through genetic mutations over the last millions of years. Many of these have wiped out large populations of living species (e.g., the Black Death). Individuals having the necessary genetic characteristics and immune systems to survive these viruses have passed this capability to succeeding generations; thus we are here today by virtue of our ancestors who have survived many diseases that have appeared throughout history. There is always the possibility, however, that a new variation or mutation may occur that could unleash harm to large numbers of individuals who have not or cannot develop the necessary defense mechanism.

A quote from the *San Francisco Chronicle* indicates the fear associated with self-replication:

> What deeply worries him [Bill Joy] is that these technologies collectively create the ability to unleash self-replicating, mutating, mechanical or biological plagues. These would be 'a replication attack in the physical world' comparable to the replication attack in the virtual world that recently caused the shutdowns of major commercial Web sites.
>
> 'If you can let something loose that can make more copies of itself,' Joy said in a telephone interview, 'it is very difficult to recall. It is as easy as eradicating all the mosquitoes: They are everywhere and make more of themselves. If attacked,

> they mutate and become immune.... That creates the possibility of empowering individuals for extreme evil. If we don't do anything, the risk is very high of one crazy person doing something very bad.' (*San Francisco Chronicle* 2000)

Consider the conditions necessary for self-replication. A virus is about the simplest self-replicating species that nature has evolved. It is constrained for nourishment to living species on which it may find the necessary nutrients and environment (e.g., temperature) for self-replication. Life as we know it consists of a rather complex array of chemical constituents. It is only through contact or some transfer mechanism (the wind in the case of plants) that a virus may be passed from one member of a living species to another. Viruses do not have the "intelligence" to create nutrients from non-living elements that they can then use to replicate; they require the rich array of nutrients found in living species. Further, viruses generally do not kill their hosts (Drell 1999), or else they would eliminate their means of sustenance. A fatal virus is typically one that is transferred from one species that has developed tolerance to another that has not.

A definitive answer does not exist today, but a reasonable hypothesis is that any self-replicating entity having the capability of sustaining itself by altering the environment (and gathering sustenance from non-living species) must be far more complex than a virus. Such an entity must be capable of gathering elements from various portions of the land, and in communicating among like entities (implying a social structure) to distribute these elements into whatever is necessary for sustenance and replication. Otherwise, a virus-type self-replicating entity will resemble the viruses we know today. This also requires a "resource" of living species that come in close proximity with one another in order for the virus to spread. In other words, self-replicating organisms are likely to resemble viruses as we know them today, or be very much more complex (and unlikely to be created except for years of advanced research far beyond any state of knowledge we have today).

The conclusion of the above paragraphs suggests that any concerns we have about self-replicating entities are likely to be restricted to those resembling the viruses we are familiar with today (and biological in nature). It is true that altering the DNA structure of a virus may produce a new species not heretofore created by the "random roll of the dice," and this is the reason for the caution expressed by Bill Joy: "Genetically engineered viruses for example shouldn't be touched." Genetic modifications that produce vaccines, however, may be considered advantageous if pursued with great care.

Taking Control

The issue of control is one of the major concerns of critics such as Bill Joy. This appears in the following (Chaudhry 2000):

> 'People are afraid precisely because there are no hurdles anymore,' Davis said. 'When you broaden the horizon far enough, there comes a point when what we know and what we can control drops away. This is very much about losing control.'

> ‘Joy, however, is more worried about what he perceives as a refusal to take control of technology. He says scientists are taking a passive attitude toward technology, abdicating their moral responsibility to make responsible choices.’
>
> ‘There is this fatalism,’ he said. ‘Like it’s all going to happen anyway, and we can’t do anything about it.’

If anything is needed, it is the presence of a responsible and respected scientific body with thoughtful statements about the reality of the options and possibilities arising from research in this area. The scientific enterprise has on occasion undertaken introspective examinations to improve public perceptions of the enterprise (Forum Proceedings of Sigma Xi 1993). Part of any analysis should include an accepted set of observations, which, if they begin to come true, represent a “signal” to give attention to developments that may represent danger as agreed upon by prior considerations. Due to the attitude expressed by many vocal participants in the debate about nanotechnology, serious discussion of self-regulation is probably due. Consider the viewpoint expressed in the following paragraphs:

> The proponents of bioelectronics are inevitably correct in suggesting that it holds out incredible benefits for the human race. (Admittedly, those who argue for human obsolescence as a benefit should be discounted by any reasonable humanist.) Likewise, it is undeniably the case that some of the skepticism toward bioelectronics arises out of the superstitious attitude that people hold toward computers and electronic technology, as well as medical and reproductive procedures that they don’t fully understand. However, they are incorrect in arguing that regulation and oversight will only hinder research in this area and prevent scientific progress in the relevant areas. In marginalizing the social and ethical issues generated by research in biocomputing, these researchers are showing a side of science that people have routinely expressed anger about — its refusal to accept social responsibility for unforeseen consequences. In order for bioelectronic research to progress, it will have to accept that the potential dangers are real, and that the concerns of some skeptics are valid. Otherwise, something disastrous might occur which might create a “death-blow” for the industry, much as has happened with nuclear power in the U.S., and nothing positive will ever have been attained.) ... (Forum Proceedings of Sigma Xi, 1993)
>
> A new “cyborg bioethics” may be necessary. While it cannot be possible to foresee all the consequences resulting from bioelectronics, most scientists are already aware of what some of the major dangers are. Researchers in biocomputing may be required to adopt protocols on acceptable research with human subjects, much as genetic engineers did back in the 1970s. In drafting bioethical imperatives for bioelectronics research, it will probably be imperative to consider the concerns of groups such as the religious community, since to ignore their concerns simply out of the insistence that they are merely acting out of “anti-science” ignorance will leave an important group “out of the loop” of this research. This is uncharted territory for the human race, and it is the first time in which our own “built environment” may be directly incorporated into our own sense of self and human nature. Our own biocomputers (the human mind) evolved under a very specific set of evolutionary circumstances, after all, and they may not be equipped with the foresight and moral sense to keep up with the accelerating pace of technology.

> Since this is the case, it is probably imperative for society to assert that the scientists and engineers charged with creating this new technology exert the proper amount of social responsibility. Safeguards will have to be insisted on to prevent the possible negative impacts discussed above, and many of these things will have to be built in at the instrumental level, since they probably cannot be achieved only through policy and regulation. Critical public awareness and vigilance, of the kind already shown by Jeremy Rifkin and the Foundation on Economic Trends with regard to biotechnology, will be essential. But ultimately, bioethicists will have to grapple with the fundamental issues involved, which touch on aspects of human existence and human nature which reach to the core of what most people think is involved in what it means to be human, and this will not be an easy dilemma to resolve. (Mizrach, no date)

Other authors, who consider the present threat from biological agents, echo the point: "We're already there!" (Drell 2000). The concerns that have been expressed about self-replicating species from nanotechnology are very similar to those expressed about biological agents that can be made today. If steps are to be taken to control or regulate certain aspects of nanotechnology (genetics, nanotechnology and robotics), many of the lessons and concerns have already been extensively considered by those struggling with the threat of biological warfare (Drell 1999).

Rational Progress

It is imperative to view potential scientific and technological progress rationally. Constraints have been imposed on research involving cloning of human embryos or subjects. It is so difficult to envision the ramifications of cloning the human species that action was necessary to place restrictions on such activity. Laboratory demonstrations involving nanotechnology, at the present stage of development, do not even begin to approach the level of impact foreseen by cloning. A current dilemma is that "visionaries" who have not been involved with laboratory research foresee events that are far removed from the reality of what is possible given the current stage of research.

Further, consider the case of chemical/biological warfare. Biological warfare clearly involves the use of self-replicating species that destroy selected forms of life. The world has seen the consequences of chemical warfare, and, in limited scenarios, the use of biological agents (Drell 1999). The horror resulting from the use of these agents has led to international agreements (Geneva Convention 1925; Washington, London, and Moscow Convention 1975). The use of such agents has been banned (agreed upon) by 142 nations (Crowe 1999), although today "there are over twenty countries with known or suspected chemical and biological weapons programs" (Mark 1999). Nanotechnology has been mentioned on occasion as a means of enhancing delivery of this threat (Hughes 1998) as well as a means of ultra sensitive detection in the presence of such a threat. Research into certain aspects of this form of warfare must continue:

> Work on offensive biological weapons is forbidden by law in the United States. However, the same is not true of many potential adversaries. Thus, it is important to have a vigorous research program to explore genetic mechanisms that can be applied to protecting our people from attacks using biological weapons. (Mark 1999)

The harm that may be caused by a "self-replicating" system is clearly one of major concern. U.S. Code* prohibits the possession or use of biological agents. Adversaries have considered a long list of such agents for use (Alibek 1999). Additional agents, be they biological or "self-replicating," would probably come under the same restrictions and controls. Self-replicating species evolving from genetic modification of DNA would almost certainly be considered as a biological entity.

A significant (but perhaps moot) question revolves around the possibility of creating a self-replicating species that is so dissimilar to those of biological agents that new legislation or international protocols would be necessary. Software versions of viruses are clearly a problem today, and are sufficiently different from biological agents that legislation is necessary. However, viruses that consume materials and are not based on biological components are unlikely to be of concern for many years.

Semantics: Facts and/or Fiction?

Much of the concern that has been generated by Bill Joy and the publicity associated with research genetics, nanotechnology and robotics (GNR) is due to visions conjured by the use of words in an inappropriate context. Scientific principles are not changing as a result of nanotechnology. Some attention to translating current-day hype in terms of accepted science would bring reality to some of the science fiction that pollutes rational thought on this subject. It is unlikely that the Laws of Thermodynamics will be modified by nanotechnology or other scientific frontiers. If there were a hint that the laws of thermodynamics might be modified when one enters the nanometer regime, this would gain a great deal of attention by a large number of scientists for scientific validation.

Consider the "dictionary" associated with the words and phrases that appear in the non-scientific world (particularly on the Internet):

Molecular machines and/or assemblers: Such entities are envisioned to perform functions "atom by atom" to create products having "every atom in its place." In reality, such devices are little more than *catalysts* involved in a material transformation (reactants to products). Ordinary laws of thermodynamics will continue to provide the guidelines of what products are possible. Diamond-like products can be produced if the Gibbs free energy of the products is less than that of the reactants. Considerable effort by researchers over decades has found a few selected conditions where diamond products can be

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* United States Code Title 18, Part I, Ch. 10, Sec.175:

(a) In General. - Whoever knowingly develops, produces, stockpiles, transfers, acquires, retains, or possesses any biological agent, toxin, or delivery system for use as a weapon, or knowingly assists a foreign state or any organization to do so, or attempts, threatens, or conspires to do the same, shall be fined under this title or imprisoned for life or any term of years, or both. There is extraterritorial Federal jurisdiction over an offense under this section committed by or against a national of the United States.

(b) Definition. - For purposes of this section, the term "for use as a weapon" does not include the development, production, transfer, acquisition, retention, or possession of any biological agent, toxin, or delivery system for prophylactic, protective, or other peaceful purposes.

produced. It is very unlikely that such products will emerge from reactants in solution at room temperature, for example. Products that can be imagined are not necessarily easy to produce by reaction pathways.

Robotic life forms, living machines, self-evolving machines: Such terms conjure visions of self-replicating species that would be a threat to life as we know it today. Calling such entities “machines” invokes the same fears of a mechanized world that challenged “John Henry,” the “steel-driving man,” who “laid down his hammer and he died.” Such self-replicating species, or “smart machines,” have not appeared in any form other than unexpected viruses that have emerged from other living species. We can expect other self-replicating species such as new viruses. We are far from any experimental evidence of other forms of self-replicating species. There should be ample time to address such a problem if any experiments begin to demonstrate effects that are science fiction today.

Self-replication: A self-replicating species is interpreted differently in various disciplines. In computer science, for example, an algorithm that is able to generate a sequence of bits representing an identical algorithm is considered to be self-replicating (Byl 1989). A computer virus is self-replicating. This ignores the hardware and energy provided to allow such an algorithm to execute. Such a “self-replicating” structure is very different from an assembly of atoms or molecules that constructs a replica of itself from “nutrients” available on earth. Semantic confusion persists when different disciplines attempt to communicate using such different preconceived concepts.

Gears: Molecular gears are envisioned rotating on “frictionless” bearings within components of a molecule. In fact, the exchange of energy between two components of a molecule through vibration-rotation interaction, particularly with proposed structures (and not produced experimentally) will have a high degree of interaction and energy exchange. They will provide a strong interaction between “moving components,” and should not be envisioned as useful components of a “machine” until experimental evidence is obtained demonstrating that point. The laws of conservation of energy must be observed.

Molecular motors: Nature has provided living cells with remarkable structures having mobility and the ability to propel themselves. The term “molecular motors” has been used to label these entities. This is currently a subject of fascinating scientific research. The functions of these molecular motors are not completely understood. It is a leap of faith and imagination to assert that “molecular motors” will be used in a manufacturing process not under the influence of the laws of thermodynamics. There is much to be gained by research with these molecules. Science fiction, imagining bizarre consequences, should not alter valid scientific inquiry until *experimental evidence* begins to suggest processes that could be harmful.

Smart materials: Biological molecular structures (including viruses) have shown an amazing capability of selecting very specific forms of interaction with selected biological counterparts. These interactions can synthesize desirable products, or destroy a living cell. The term “smart materials” has been used in describing such molecules. A leap of faith deduction has led to concepts that such molecular structures could have extraordinary computer capabilities, and larger molecular structures could form the nucleus of an intelligent life form. It's true that an ant is a small living species with programmed behavior that exhibits even asocial behavior. An ant is based on biological principles, and does not violate any laws of thermodynamics. It has a rather limited brain, does not contain a very smart "computer," and is very limited in the behavior it may exhibit. Just how much "intelligence" can be contained in a given volume or mass of material is a question we don't know how to answer today. However, using the term "smart materials" for molecules with very selected functions should not be confused with "intelligent sophisticated computers."

Visions of "computers the size of a pinhead" have been propagated by members of the nanotechnology community to a lay public that does not understand the concept of smart materials. When the public hears these words, visions of machines (as they know them, with metallic gears, motors, etc.) coursing through the body cause great concern. Part of the problem has been the terminology used by "visionaries" in attempting to gain recognition for their efforts. These "visionaries" would be better employed by the filmmakers in Hollywood. Part of the problem is that institutions have been set up to further disseminate (or popularize) these views, to sponsor meetings, or even to attract venture capital. The nanotechnology community must be concerned with their image if Wall Street finds a lack of credibility associated with these commercial practices.

A responsible scientific community would be able to influence responsible scientists to use terms with specific meaning that are not emotionally loaded to please newspaper reporters. The mass media (newspapers, magazines, Internet Webmasters, etc.) have a responsibility to verify and validate statements made by alarmists. This should be pursued by the responsible community as part of an effort to reduce public concern over non-existing threats.

"The World is Coming to an End!"

Throughout history there has been a tendency for peripheral elements of society to feel that the world is coming to an end. The cartoon of a man in rags carrying such a sign is legend. Isaac Asimov has addressed many possible catastrophes leading to the end of humanity in his book, *A Choice of Catastrophes* (Asimov 1979). He would be amused at yet another variation to the many "choices" outlined in his book. A writing in 400 B.C. represents early concerns that have been with us as long as humanity has existed:

> Alas for the day! for the day of the Lord is at hand, and as a destruction from the Almighty shall it come. (Asimov 1979)

Critical Experiments or Observations

At the present stage of research in nanotechnology, little concern about "self-replicating life forms" exists among scientific investigators. Most of the fear expressed today comes from individuals influenced by a "virtual unreality" generated by "visionaries" who have taken free license to imagine both the best and the worst of what is conceivable (and not even possible). However, it is time to ask the question: At what point is it appropriate to express concern and for the government to develop guidelines over limiting research that may be potentially threatening to society? This subject may be discussed extensively.

A set of experiments, if demonstrated, could represent the stage at which social concern may be appropriate. The following set is offered as a beginning for discussions on this subject. Such a set should be examined and reformulated by responsible individuals until an appropriate set can be agreed upon. These can be reformulated as we learn more about the nature of the chemical, biological and physical world. Consider the following potential developments in nanotechnology. If in the course of nanotechnology research and development, laboratory experiments begin to reach the state indicated below, it is time to consider that such achievements may be subject to control if pursued to greater sophistication, in order to reduce the threat to society:

1. *Consumption of Resources:* Self-replicating species could possibly be produced that, if released, could uncontrollably consume resources required by a living species, or represent a threat to a living species outside of a laboratory. Note that computer viruses come under this same concern. Computer viruses consume information and time for individuals. The fact that computer viruses have been demonstrated represents a far greater threat than an imagined self-replicating robot that is only faintly conceivable in the distant future.

2. *Inadvertent Production of a Threat:* Self-replicating species (and this includes biological species) can be made that have a DNA sequence unlike that of existing species through a "roll of the dice" combination just to "try something different." This is particularly true of species that may resemble viruses, bacteria, or "life forms" that are known to represent threats to life. Such "random" experiments with new forms of living species should not take place.

3. *Computing Machines No Longer Responding to Humans with Programmed Predictability:* Assume that computer or logic functions can be made whereupon such computers are no longer completely responsive to human control (recall the computer "Hal" in the film "2001"). Such systems would be considered inappropriate for design or production. This is not meant to preclude computers with artificially intelligent algorithms, but rather to computing machines that have a "mind of their own."

4. *Devices Lulling Humans Into Acquiescence:* Any combination of computers, robots, and self-replicating species that appear to take over human functions and simultaneously lull human activity into acquiescence (or a subordinate roll) should be considered a threat. Some have suggested that television already falls in this category. A level of "control" by a device is the main issue to be dealt with.

5. *Inexpensive Products Used to Unduly Influence:* Any material, device or organism that can be used to "unduly" or "illegally" influence one individual, group or nation over another should be considered a threat to society. Weapons of mass destruction (nuclear, chemical and biological) come under this category. Mass indoctrination is another. That is why such overwhelming attention is given to these weapons. Materials, devices or organisms that may be fabricated and used by terrorists to influence others come under this same category. If small groups can inexpensively produce sophisticated products having "undue or illegal influence," this becomes a subject for attention and potential legal action and/or restrictions.

Recommendations

1. *Enhanced Defense Systems:* National Defense will be significantly enhanced by a nanotechnology S&T program. Many aspects of current high technology defense systems and procedures are envisioned to have improved capabilities with the anticipated products of this field. Advanced technology is a key element of our national security; we therefore must pursue this subject vigorously. As a means of emphasizing the most relevant aspects of nanotechnology S&T for this purpose, strong support within laboratories emphasizing national defense missions is most appropriate.

2. *Address Integrity of Nanotechnology:* The nanotechnology community should, in an appropriate forum, address the misinformation about the subject that appears in the popular press and the Internet. A lack of scientific discipline associated with many hypothetical products of nanotechnology can negatively impact the integrity of the science and the image of the field. This forum should address the hyperactive misperceptions about self-replicating species. Issues should be recognized that might be different (if any) from those already faced by the current threats from biological agents.

3. *Address Societal Impact of Nanotechnology:* An appropriate forum should address the potential impact of the anticipated products of nanotechnology on society. This should take the form of searching for agreement on a set of experiments or observations which, if found to be true, would represent capabilities that are not in the best interests of society. These observations and issues should include ethical and moral as well as threat questions.

4. *Distributed Resources Lead to Greater National Security:* To the extent that nanotechnology provides enhanced resources in the form of (1) new systems, (2) increased capabilities of existing systems, or (3) reduced costs for the performance of existing capabilities, this represents an increase in available resources for the world. With increasing resources distributed worldwide, tensions between nations and groups tend to be less, resulting in enhanced national security for all. It is also noted that nanotechnology is being pursued vigorously worldwide, enhancing the opportunity for worldwide distribution of the benefits of research in this field.

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