the art of the invisible: achievements, social benefits, and challenges of nanotechnology

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The history of science and engineering as an important social force is relatively short. Most would date it to the Copernican revolution of the sixteenth century, i.e. for less than a quarter percent of the time we have existed on this planet. With the advent of the scientific process—using abstract agnostic tools of mathematics, questioning, postulating, theorizing, predicting, verifying, believing enough in theories to go ahead but doubting enough to notice errors and faults—came the modern approach to learning and invention. Overcoming dogmas, even in the face of contradicting observations, has always been a challenge to society and always will be; the comfort of "business as usual" can't be overstated. This holds true in scientific endeavor too. But the physical and life sciences, with engineering and medicine as their professional areas of practice, are among the few undertakings where revolutions can happen relatively easily. Einstein's theory of relativity—the "absoluteness" of the speed of light and gravity as a deformation in space-time; quantum mechanics as an entirely new mechanics to describe reality that is based on probabilistic approaches—indeed the philosophical understanding of reality as a result of observation; Gödel's theorem of the limits of provability within any axiomatic system; the genomic decoding of the basis of life and the understanding of metabolism, replication, and reproduction, these are ideas that were rapidly adopted in the technical community as they stood the test of the scientific approach.

The scientific pursuit of truths and the drive to apply truths know no national boundaries and adapt to contemporary conditions. Among the progenitors of the dawn of scientific civilization, Copernicus was an ecclesiastic and from Poland; Bruno, who paid with his life for standing up for his beliefs against the dogma, was primarily a theologian and from Italy; Tycho de Brahe, a court mathematician from Denmark; and Johannes Kepler of Germany and Galileo Galilei of Italy teachers. Not all pioneers of science were teachers, even though universities as institutions of learning[1] had existed for a long time. In the last century, Albert Einstein started as a patent clerk and Neils Bohr's contributions came from his nomadic style at his center at a state-supported home institution, not unlike Copernicus and Kepler. In current times, as the power and economic impact of science and engineering have grown dramatically, numerous research institutions have come into existence, started by scientists themselves,[2] and were either self-funded or funded by philanthropists and others who are a kind of modern royalty: venture capitalists and small company founders who have gained fortunes through the applications of science

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In the East, Nalanda University spanned the 5th to the 12th centuries AD. The oldest continuously operating university, the University of Al-Karaouine, Morocco, was founded in 859 AD, and the oldest Western university, the University of Bologna, in 1088 AD. The early universities arose from religious institutions and gained increasing independence as the power of the religious hierarchy declined.

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J. Craig Venter, who was an important participant in sequencing of human genes through the Celera Genomics company, now heads the J. Craig Venter Institute, a self-funded research entity, whose most recent success has been a significant step towards building an artificial cell. Leroy Hood, who was among the early pioneers in tools for molecular diagnostics, heads the Institute for Systems Biology, an independent institution. These approaches are not unlike those of Thomas Edison, Graham Bell, or Nikola Tesla at the turn of the nineteenth century.

and engineering. Universities, as in the past, play a part, but are not the sole institutional agents of progress. State-funded laboratories, independent laboratories, and industrial laboratories, particularly for biological sciences, are all involved in the discovery and applications enterprise.

A scientific revolution originates with unique individuals of incredible will and inner strength, people who create an immense centripetal force in the form of a central simple vision as a universal organizing principle.[3] Scientific progress, a period of consolidation, happens because of individuals who pursue many ends centrifugally, employing a variety of tricks to take advantage of the connections centered on the organizing principle in a world full of complexity. Scientific and engineering progress relies both on the central discovery and the ensuing complex assembly. Mendeleev's creation of the periodic table before atomic particles and atoms were known or observed, Darwin's evolutionary principle formulated without any molecular, genetic or organismic knowledge, and Heisenberg's creation of quantum mechanics overthrowing Newtonian determinism are all instances of overturning dogmas and creating new principles.

It is humbling to realize that chemistry, biology, and physics, as we know them and use them today in engineering and medicine, by and large, didn't exist just a century and a half ago. From the discovery and understanding of chemical elements quickly arose our ability to make ammonia, and from it agriculture-enhancing fertilizers that make possible existence of nearly seven billion humans on earth. Genetic interactions and evolutionary understanding of mutations are central approaches in fighting disease and healthier and longer life. Computing and communications, which depend on electronics, draw the principles of operation of their hardware from quantum mechanics and information theory. We are enormously fortunate to live in an age of discovery and the adventure of applying those great discoveries.

Centrifugal advances also depend on the availability of tools—instruments of observation and creation. The smaller the tool, greater the likelihood of it being personalized, individualized and humanized, i.e. made friendly for individual to use. Because of this quality, tools are used by many, thus stoking the creativity of a larger collection of scientists and engineers, in turn affecting a larger group of society. The water wheel evolved into the steam engine, later into the electric engine and the combustion engine. Each one came in many forms. The combustion engine drives the airplane, the car, and the scooter in various incarnations. The electric engine runs the train, the air-conditioner, and even the hard disk drive of the laptop computer. We know now that there exists an engine of molecular life—the ATP engine called ATP synthase. It converts chemical energy to mechanical motion within our bodies. Who knows what doors this discovery and its synthetic laboratory creations will open? But, the constant theme in this miniaturization process has been to find applications that are useful to us as humans. Hospital operation procedures have changed dramatically due to endoscopic tools; in most cases, hospital stays are now eliminated. The mobile phone and other communication instruments are everywhere, even in the poorest regions of the world, arguably bringing the greatest benefit there through easier and open information exchange. Personal software for writing, drawing, and visualizing abound on our small computers. In all of these, miniaturization and personalization have had a spectacular impact.

Technological progress of course also has its dark side, depending on the innovations themselves and on the ways they are diffused and used. Fertilizers, computers, and combustion engines all consume enormous amounts of energy,[4] are sources of pollution, and have imbalanced our world. The Industrial Revolution in Europe drastically reduced the average human life span. Much of the energy consumed in the world today took billions of years to accumulate on our planet, making possible seven billion humans instead of perhaps a billion, but in turn affecting global climate. Personalized tools have a major impact through a multiplicative effect. Cars are a good example, but so is the cell phone. Each new creation, and the new ways in which society as a whole and its individuals interact, creates a new divide between the haves and have-nots, between those who adapt and those who don't, those who learn to take advantage of the tools economically and socially and those who don't. So, while average wellbeing may rise, disparities also usually rise. Because technology often eases manual tasks, those on the bottom rung of the economic ladder potentially suffer the most from new technologies.

It is in this societal context that we now turn to the promise and challenges of a burgeoning new area of technical specialization: nanoscale science, engineering and technology—often shortened to "nanotechnology." Fundamentally, nanotechnology is a phenomenon of a size scale—a dimension. Like biology that encompasses a very large breadth of life science areas, nanotechnology has an impact encompassing the breadth of science, engineering, and technology that the nanoscale dimension affects. Perhaps some time in the future we may choose to call it "nanology"

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To quote Arthur Koestler, "The more original a discovery, the more obvious it seems afterwards."

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The fertilizer and information industries are each claimed to use nearly 10% of the world consumption of energy, and the combustion engine even more.

to reflect this breadth, rather than just referring to nanotechnology, nanoscience, and nanoengineering.

If we take any bulk material that we can see with our naked eyes—whether the material be hard or soft, inorganic or organic—and make it smaller, it still has the same properties. A large piece of diamond, iron, plastic, or rubber has the same properties as a small piece of diamond, iron, plastic, or rubber, and we use these materials and their reproducibility to great advantage where these properties are effective. Bridges can be large and small—carry a single vehicle lane across a stream or a massive train across an ocean channel. Plastic is used in car panels and in little watches. On the other hand, if we go to the extreme end of reducing a material's size, i.e. their atomic or molecular level, the smallest size at which we could identify them, their properties will be entirely different. An atom or a molecule has properties that arise from the quantum mechanical interactions that lead to their existence as stable units. Carbon, an atom, forms diamond, but it also forms graphite, and is also the major constituent of soot, the result of inefficient combustion. All of these bulk assemblies of carbon have different properties.

So, in going from the atomic scale to the bulk scale a large change takes place in the properties. This happens in the nanometer size region. The properties of materials and their physical and chemical interactions arise from the forces of nature—the atomic or molecular bond is a result of quantum-mechanics and electromagnetic forces. Through interactions of and between atoms, molecules, electrons (the carriers of charge), and photons (the carriers of light), physical, chemical, and biological processes undergo a dramatic transformation in properties at the nanoscale dimension. This dimension range bridges the atom and molecule at one end and bulk materials at the other. The reason for this is that the forces at the center of these interactions, the forces that result in the characteristic properties, are fundamentally nanoscale in nature.

And the property changes at the nanoscale are not simply small. They can be dramatically different—new properties emerge, ones to which we did not previously have access at either the macro or micro scales.

Quantum mechanical tunneling is one phenomenon that has been employed successfully in the past decade: in semiconductor memories that don't lose their data and have no moving parts, those used in the camera, in the cell phone, and in the thumb drive. In these devices, electrons are simply made to tunnel through an insulating region at low voltages. It happens because of the wave nature of the electron and the ability of the wave to penetrate small distances—nanoscale distances—in an insulator. Such fundamental properties as melting temperature, magnetization, charge capacity, etc., can all be altered without changing the chemical composition of the material because of this wavelike property and the interactions at the nanoscale. Because of this wave nature, interactions between electrons and light can also change at the nanoscale—a property that medieval glass blowers utilized dramatically in stained glass. Stained glass often uses nanoscale particles of gold or silver. These particles provide red, blue, green, brown, or other colors by enhancing the scattering of that color depending on the particle's size. The electrons in gold or silver nanoparticles interact with photons of light creating the color. Scientists describe this collective interaction between electron plasma and photons through a particle that they call a "plasmon." The glass blowers had unknowingly developed the technology for precipitating them controllably in that size. The light that is carried in optical fibers that makes fast data communication possible is generated using lasers that are very efficient light sources through enhanced electron-photon interactions arising at the nanoscale in artificially created quantum wells. Even the optical fiber uses light confinement at the nanoscale to move it with limited loss over long distances.

Chemical reactions result from interactions between atoms and molecules in their neutral, excited, or charged states. The reacting species need to come close together and have energetically favorable pathways for the reactions to be effective. Catalysis is central to providing this effectiveness: a catalyst, while chemically unchanged, provides a low-energy path to increasing reaction rates. It does this by mediating via a surface where molecules come together, attach, and react with each other in energetically favorable conditions, leaving the catalyst undisturbed at the end of the reaction. As one approaches smaller dimensions, the surface area to volume ratio increases—a nanoscale effect. A significant non-linear enhancement in this simple property makes catalysis enormously effective. The Haber-Bösch process for making ammonia, a key ingredient for making fertilizers, productively uses catalysis in a number of steps. Hydrogen is derived from methane in natural gas using nickel oxide. Ammonia is then formed from this hydrogen and nitrogen using iron, derived from magnetite, with an ultimate conversion efficiency of 98%, i.e. nearly perfectly.

Magnetite, a form of iron oxide, is a material whose nanoscale properties have been utilized in nature for orders of magnitude longer than the glass blowers. Magnetite is magnetic. As a collection of nanoscale crystals—arranged as chains, thereby allowing the collection to become a highly sensitive magnet—it endows organisms with the property of magnetotaxis, the ability to discriminate the magnetic field lines of the Earth. So, *Magneteospirillum magnetotacticum*, a bacterium found in ponds and first isolated in 1975, along with many others, is magnetotactic because at the small scale, in the form of a collection, deviations from Earth's field lines can be discriminated by the primitive organism. Many animals use this magnetic information for navigation, including pigeons, loggerhead turtles, and spiny lobsters. In the evolutionary process, nature evolved ways by which inorganic nanocrystals could be formed in largely organic systems, something we are still learning to do controllably in the laboratory. Another interesting nanoscale example from nature is the iridescent color of some butterflies and peacock feathers. These are nanoscale optical interference effects from the three-dimensional structures that nature builds, and that, in the laboratory, we have only recently taken the first steps in recreating. Biological phenomena tend to be immensely complex, resulting as they do from a combination of the randomness of events and a large number of interactions that happen between larger numbers of entities, under the influence of local forces. The phenomena are sensitive to initial conditions, small perturbations, have a large number of interacting components, and often a large number of pathways by which the system can evolve. If a human has insufficient energy input, i.e. hasn't eaten enough, the body knows how to slow down the metabolism. Unlike much of what we do in physics, chemistry, and engineering, this is immensely more complex, involving a variety of interactions at various scales. That simple and complex organisms have developed approaches to making nanoscale single crystal magnetic domains to achieve these properties is a tribute to nature's resourcefulness and biology's cleverness—characteristics that the human species discovers regularly.

The last few decades set the stage for the development of condensed matter science and engineering where small, personalized tools became pervasive, and where the ability to control and observe at the nanoscale became available to a large community. These tools allow us to assemble, manipulate, control, probe, image, and look at a myriad of properties at the nanoscale. Of the tools, the scanning tunneling microscope and the atomic force microprobe have garnered the most press. But, just as significant have been many of the fabrication tools that let us define, pattern, and connect at the nanoscale dimension: new techniques for visualization, tools that allow us to self-assemble monolayers on surfaces, tools that let us synthesize, and in general tools that let us do this reproducibly, cheaply, and quickly. We can now synthesize atom by atom, and we can also sculpt to get down to near the atomic level. We can probe phenomena that exist at this scale through a large toolset that gives us a variety of views. And because the properties change dramatically when one gets down to the smallest units, we can leverage those properties by utilizing assembling and sculpting techniques. This in turn has made it possible for a large community to reach down into the nanoscale world. The nanoscale is a dimension, not a discipline, and the properties at the nanoscale show up in and are connected to all the disciplines. The profound impact of this, through the open large-scale participation of the community and the breadth of disciplines, has been that a large new area of interesting and exciting work has grown at the interfaces. Engineering, physical, and life-sciences have commingled like never before. And this has led to immense progress and utility that could not have been foreseen even a decade ago.

A few examples of this breadth, at the heart of human existence, will illustrate this point. Let us look at some of the challenges facing the world. Major ones revolve around being sustainable—a large complex community of humans and millions of other species living sustainably, i.e. in equilibrium with each other and with the wider natural world. Energy, better health, equity and alleviation of poverty, education and conservation all immediately come to mind as unifying themes for sustainability. Some sustainability-related questions immediately arise: can we lower energy consumption—in transportation, lighting, food production, and other facets of living by recreating our environment (heating, cooling, and aesthetics) and communications (in information exchange, in computing, and all the mobile instruments)? Can we help with water problems by producing clean water, removing heavy metal impurities such as arsenic and reducing water use? Can we improve agriculture productivity by producing plants for healthier diets that are more disease resistant and that consume less energy and water? Can we provide more efficient carbon sequestration through physical and biological approaches? Can we improve management of forestry resources by using less paper and introducing better paper production techniques? Can we improve on health care by introducing cheaper and earlier diagnosis, detect contamination, cure diseases, improve on treatment or slow degenerative diseases, and attack the most pernicious of the diseases—malaria and cancer? Nanotechnology holds promise for addressing all of these sustainability-related issues.

Strength of materials and the properties of surfaces of materials are in use all around us. Polymers, whose widespread industrial-scale synthesis started in mid-twentieth century, became ubiquitous by the turn of the century. Some would argue that plastics were the backbone of China's industrial revolution and a key to the transformation of everyday life, from children's toys to the widespread use in home and office and in ubiquitous packaging. Plastics and polymers achieve their properties through surface interactions of chains of hydrocarbons. Both of these are affected by new nanotechnology inventions. Carbon nanotubes, based as they are on a strong carbon bond—a different configuration than that of diamond—provide strong intrinsic and surface interaction properties; they can withstand stronger forces than steel of similar dimensions.[5] Pull them into strands similar to the way polymers are employed, and one gets materials of great strength. Carbon nanotubes are now introduced into plastics to make them more resilient, for example in sports equipment such as tennis rackets and golf clubs. Composites, such as concrete, fiberglass, and Kevlar are combined materials that achieve strength through the surface interactions. Concrete can be made much lighter and still maintain its strength through use of cenospheres, the hollow alumina and silica structures akin to carbon buckyballs, found in the ash of coal power-plants. The strength of nanoscale material and the strong interface allows these composites to be stronger than was possible before.

The surface is critical to this property.

We mentioned catalysis, and its centrality to the ammonia production process, as one of the major breakthroughs at the turn of last century. Today, zeolites play a similar role. These are microporous solids that are efficient catalysts based on oxides of aluminum and silicon. Millions of tons of them help fracture petroleum into gasoline and numerous other hydrocarbons, making the impact of oil less environmentally destructive.

Advances in nanotechnology seem likely to lead to major gains in energy production, energy consumption, communication, and health promotion. Let us consider some notable developments in these areas.

Fuel cells, batteries, photo-electro energy and electro-photo energy conversion are examples where efficiency improvements connected to energy are happening rapidly through new materials, thin membranes, and efficient conversion processes. Light sources made out of semiconductors are highly efficient, factors of ten better than the incandescent light bulb, and are reliable and longer lasting. We see them today in traffic lights, but we will see them increasingly in general lighting as issues of cost and of satisfying human color spectrum preferences are resolved. Light sources are also being created from organic materials, though in this case, the challenge of achieving reliability is considerably higher. Photovoltaic generation is also benefiting from efficiencies realizable at the nanoscale. A new type of solar cell that is starting to make the transition from laboratory to manufacturing is the Grätzel cell. These cells use nanocrystalline titania, dies, and organic materials for electron transport to achieve a few percent of efficiency in energy conversion. Titania is a material found in paint, sandpaper and many other places where its strength is utilized. It also absorbs photons efficiently and hence is also employed in suntan lotions. The new photovoltaic structures use low energy processes in fabrication, unlike the more popular current silicon photovoltaics, making the cost and energy used in fabricating them small. The enhanced surface interactions can be used to reduce contamination. In heavily populated regions such as Asia's Gangetic plane, with the dropping of the water table many deeper wells now being used for hygienic drinking water are naturally contaminated by large concentrations of arsenic. Improved efficiency of electrochemical processes on the surface allows the arsenic to be efficiently scavenged with iron oxide nanoparticles.

Electronics, computing, and communications have benefited tremendously from the properties of the nanoscale, a scale where wave electron and the material interact in many ways to produce interesting properties. Consider, for example, the case of data storage. Every day humanity is creating more data than the total amount of data that was stored just twenty years ago. Non-volatile semiconductor storage is utilized in our cameras, phones, miniature music players, and for storing and exchanging information. These work because tunneling, a quantum mechanical phenomenon, takes place at the nanoscale. The large amounts of data that Google searches and that enterprises store away have become possible because magnetic disk drives store more in a smaller area, i.e. are more compact and also cost less. This becomes possible because the ability to sensitively read and write has improved by taking advantage of the electron spin and field interactions that occur at nanoscale. Our fast communications infrastructure is dependent on optical transmission. The small

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There is currently a communicable disease infecting the science community: over-exuberance in claims that border on incredulity. This disease that has always been around is particularly pernicious because the breadth of the disciplines makes it difficult for many to see through the wild claims. Perhaps some of this is a societal and ethical issue as much pressure is put on scientists to justify their research. There is also a school of thought that young people can be inspired to pursue science and engineering through excitement that mostly relies on over-exuberance—an approach that has Sbecome easier in these times of the Internet, short attention span, and the ease in creation of wild visual imagery through personalized software. The application of carbon nanotubes for space elevators is one such myth (see "The space elevator: going down?" in *Nature Online* published May 22, 2006, and available at http://www.nature.com/news/2006/060522/full/news060522-1.html). Similar claims abound regarding the use of molecules and other atomic-scale approaches in electronics.

laser diodes and amplifiers and optical fibers employ confinement of carriers and photons in small dimensions for large-scale improvement in efficiencies in signal generation and transmission. Smaller devices also consume less power, so energy consumption per device has also decreased over time. However, the personalization of small instruments (e.g. computers) has also meant that more people are using them. Hence absolute power numbers have not decreased.

This precision sensing and control applied widely in electronics has also been a major determinant of how nanotechnology is being applied in biosciences. One of the fundamental challenges in biosciences has been the detailed understanding of phenomena under the specific chemical and physical conditions that exist in real environments. When polymerase chain reaction (PCR) was invented, it provided a technique to amplify a piece of DNA of interest and thus have more copies at one's disposal for study and analysis. In a small tool, PCR made it possible to generate millions of copies of a desired strand of DNA, and use them for genetic manipulation. Similar gains were made by use of microarrays, monoclonal techniques, and use of fluorescent proteins. Much biological experimentation, however, continues to depend on statistical analysis of data where a large collection of such interactions is taking place, and one extracts from it possible models to describe the specificity. Physical sciences techniques tend to strip away most of the extraneous phenomena and simplify a system so that the phenomena and properties of interest can be studied rigorously. With the advent of many nanoscale techniques, techniques that get down the smallest scale, it becomes possible to start unraveling the secrets without having to resort to statistical analysis and we can now study all the possibilities comprehensively.

Doing so, however, requires ultra-sensitive sensors. Size control allows one to make a wide variety of ultrasensitive sensors. A fluorescent molecule can be replaced by a more robust optically active nanoparticle tuned to specific wavelength for response, and tied to a molecule whose chemistry is being studied. One can use the plasmonic (electron plasma—electromagnetic) interactions to achieve localization of heating through the local coupling of energy at nanoscale dimensions. Cantilevers can be reduced down in dimension to a point where single-atom weight sensitivity can be achieved through observation of frequency shifts. Nanotools can be made to isolate, control and grab, and build scaffolds to organize cells, grow cells, pattern cells, and probe cells in two-dimensional and three-dimensional assemblies. It is possible to use optical tweezers to grab nanoparticles, move them around, and if desired study the various possibilities of reactions with molecules that are tethered to them. So one can imagine putting nanoparticles and other machinery to observe and interact *inside* cells and in tissues and do real-time sensing and imaging and unravel the complex workings inside the cell itself. One can work with these tools under realistic conditions of interest because of the large improvements in sensitivity, imaging, and control that nanoscale has provided.

Scientists tend to overestimate what can be done over a short time horizon—about ten years—and to underestimate what may be possible over a long time horizon—fifty years. What is very interesting in nanotechnology is that, because of its foundation in the important nano-length scale, its reach across disciplines is extensive. Never in the past have researchers generated knowledge so widely applicable across technical disciplines. The last decade has been a good start. But, as the tools and understanding develop, many new uses will be opened up that will be made possible by the knowledge at the boundaries of disciplines. Progress should continue to accelerate in the physical science and engineering space where photovoltaics, lighting, energy-efficient computing, information storage and retrieval, and communications should all continue their forward march. It can reasonably be argued that chemistry and materials science have focused on nanoscale phenomena since their inception; after all catalysis or synthesis of molecules, preparation of composites, and hard coatings have been around forever and draw on nanoscale interactions. What is new is that sensitive tools give us the ability to understand these phenomena better. New techniques for synthesis—of membranes, nanocrystals, and new material forms—should help improve technology in major areas of societal needs, such as fuel cells, energy storage, and contamination removal. The use and development of nanotechnology tools are very much in their infancy for life sciences. For use by the life scientists, the tools need to become more user-friendly, a systems-design task, but one that could enable cheap and quick decoding of the genetics of a complex organism, and diagnosing and delivery of drugs locally through nanoscale encapsulated systems, so considerably advancing preventive medicine.

Before closing, we return to the discussion of the societal consciousness of science and engineering, and specifically nanotechnology. The social problems and issues we encounter are no different, arising as they often do from humans and institutions attempting to "succeed." In the life sciences, there has been a greater societal awareness because of, among other reasons, the influence of pharmaceuticals in contemporary life and because of the relatively easy way havoc happens: witness anthrax, Vioxx, smoking, and thalidomide, each contributing growing social awareness. Practitioners working in the physical science and engineering worlds also need to develop approaches so that the research and development process remains ethical and holds the greater good of society paramount.

Because it has this vast reach, particularly in health and environment, Nanoscale research needs to be conducted in accordance with sound ethical values and principles by means of ethically responsible practices.

Here are a few potential landmines.

Inexpensive information connectivity, together with vast informational storage, and the capability and inclination of individuals, groups, and states to snoop, is a potential nightmare that has intensified over the past several years in the Western and the Eastern world. Nanotechnology enhances this potent capability. How should society and research work out this dilemma?

Humanity is the first evolutionary creation capable of changing the path of the survival of the fittest. What is the relationship between humans and nature? Should we acknowledge and defer to the primacy of nature? Is it ethically permissible or responsible to modify, even to entirely reconstruct natural organisms? When we replace or augment living parts, where is the boundary between the human and the machine? The time is likely not far off when neural sensors will uncover the workings of human emotions, personality, and perhaps even consciousness. In courts in India, functional magnetic resonance imaging is already being accepted as evidence of truthfulness and lying. Using neural actuators, in laboratory experiments monkeys have been electronically guided to peel and eat bananas. The Joy-Dyson[6] debates centered around the primal fear of such potent new technology arriving prior to societal readiness to manage it safely and equitably.

Should work in these directions connected to nanotechnology be halted or hamstrung because of controversial ethical issues or scenarios of possible disaster, as some have suggested? It is our view that the issues should be clearly identified and carefully considered. This should be done concurrently with continuing research and development imbued with responsible practices. Equally important is providing opportunities for practicing and future workers in the area, who are currently students, to look reflectively at their work in the context of the society in which it unfolds and which it shapes.

The importance of safety in handling and using nanomaterials, given the possibilities of health and safety hazard due to the enhanced nanoscale reactive properties, comes through in a recent survey[7] of nanotechnology researchers. Safe practices are also a matter of laboratory and community cultures. Considerations of time, money, status, and competition can press researchers and managers to cut corners. Historically, in most areas, governments have usually done the minimum amount necessary until pressured by those who have been or may be affected. Regulation has been a trailing edge in the safe operation of coal mines, textile factories, tire production plants, asbestos, glycol and other chemicals in the semiconductor industry, and lead in paints and gasoline. We are still debating the possible role in the increased incidence of brain cancer in cell phone users due to electromagnetic interactions nearly a decade after their widespread adoption in the developed world. Many in authority still do not recognize the role of humans and green house emissions in global warming. While nanotechnology is likely to play an important role in pollution prevention, e.g. by facilitating the removal of arsenic removal and cleaning of water, nanomaterials can also potentially introduce pollution. Silver is used as an antibacterial agent in the health industry, is employed in band-aids, and is being increasingly used as a microbe-killing agent. How much of this material is entering the water system as a result of washing?[8] Given the large amounts of money being invested in development, pressures for quick environmental regulatory approval without sufficient scientific check will be intense. While these risks are the result of shortcomings of societal procedures and processes, not in nanotechnology *per se*, nanotechnology researchers should bear them in mind.

For it is a fundamental ethical responsibility of scientists and engineers to attempt to prevent harm while carrying out their professional endeavors. Beyond promoting laboratory safety, preserving data integrity, recognizing contributions through due credit, and respecting intellectual property rights, does the researcher have any responsibility vis-à-vis the social consequences of research? The atomic bombing of Hiroshima and Nagasaki during the World War II set in motion a long period of introspection and public involvement from scientists in the societal debate;[9] how does one control a genie let out of the bottle? In the traditional view, society at large, not the individual researcher, is ethically responsible for what is done with the generated knowledge. However, the individual knowledgeable researcher also bears

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See F. Dyson, "The Future Needs Us!" in the *New York Review of Books*, vol. 50, no. 2, February 13, 2003. Emergent behavior, i.e. unpredictable behavior, appears in complex systems, i.e. those with a large number of interacting elements. Crowd behavior is an example of this. It is a very appropriate subject for thoughtful discussion and debate for man-made creations that can take a life of their own. However, one example of this that drew inspiration from nanotechnology and attracted a lot of popular attention—Michael Crichton's book *"Prey"*—is founded on faulty science. Particularly powerful is the description of swarms of nanorobots that take over bodies and the environment, that can fly and swim rapidly like insects and other similar, larger living objects. This is not possible because the viscous drag on the increased surface area slows nanoscale objects. It is like humans trying to swim in molasses.

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R. McGinn, "Ethics and Nanotechnology: Views of Nanotechnology Researchers." *Nanoethics*, vol. II, no. 2, 2008.

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See http://pubs.acs.org/cen/news/86/i15/8615news1.html. The impact of nitrogen and phosphorus as runoffs from large-scale use of fertilizers can be seen in most of the Western world. In the East, the poorer parts suffer from the disappearance of the water table (and backfilling by salt water near coastlines), and deeper wells that reach into arsenic contaminated tables, such as in West Bengal in India and in Bangladesh. This massive water depletion happened as the two-hundred-year-old invention of the diesel and electric motor became a personalized tool in the third world.

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Science and scientists rarely serve as inspiration for art. "Doctor Atomic," a popular opera that premiered in 2005, drew thoughts from the Manhattan project, in which the Atomic bomb first became reality. The nation's leading scientists of the day and Robert Oppenheimer, their leader, debated the bomb, even while they frantically worked on the weapon that Oppenheimer, the central character of "Doctor Atomic," quoting Bhagwat Geeta, later

termed "I am become Death, the shatterer of worlds." It is interesting to note that the firebombings of WWII killed many more innocent people. In later overt and covert wars, Agent Orange, depleted uranium, cluster bombs, and land mines have left a large thumbprint in time without similar societal reaction, probably because such perniciousness is spread over a longer time.

some responsibility. Researchers cannot always plead ignorance of the risks posed by the powerful 'engines' they create. Contemporary researchers develop and facilitate the diffusion of their creations in societies whose character they know. While it is not always foreseeable that particular fruits of research will be turned into ethically troubling applications, at times this is the case (e.g. when there are substantial military or economic advantages to be gained even if ethically problematic effects are foreseeable as a byproduct). Hence, if researchers have reason to believe that their work, or work in their field, will be applied such as to create a risk of significant harm to humans, they have an ethical responsibility to alert the appropriate authorities or the public about the potential danger.

These preceding examples and brief discussion of responsibility point to the difficulties that arise when rapid scientific advances with major societal implications unfold rapidly and the society has to find the balance between fostering productive research and development activity and sustaining an effective regulatory and safety framework. One response to this challenge in recent years is the increased societal pressure for the contemporary researcher to acquire a hybrid competence: technical virtuosity wed to a sensitive ethical compass. In the words of Samuel Johnson, "integrity without knowledge is weak and useless, and knowledge without integrity dangerous and dreadful."

For practicing scientists and engineers, one of the pleasures of their discipline is that great science leaves us unalone—content and emotionally happy to have found a piece of truth that one can call one's own. Creative engineering gives the pleasure of coupling scientific discovery to the joy of having brought into the world a creation for the common good. At their best, these enterprises embody the ideals of a civilized life: the search for truth and the practice of good citizenship. Nanotechnology is in this classical tradition; it is here, it is growing vigorously, and, with prudent stewardship, will move human society forward in innumerable welcome ways.