etc group
action group on erosion, technology and concentration

Communiqué

January/February 2003 Issue # 77

Green Goo:
Nanobiotechnology Comes Alive!

***Issue*:** If the word registers in the public consciousness at all, "nanotechnology" conjures up visions of itty-bitty mechanical robots building BMWs, burgers or brick walls. For a few, nanotech inspires fear that invisible nanobots will go haywire and multiply uncontrollably until they suffocate the planet – a scenario known as "Gray Goo." Still others, recalling Orwell's *1984*, see nanotech as the path to Big Brother's military-industrial dominance, a kind of "gray governance." Gray Goo or gray governance – both are plausible outcomes of nanotechnology – the manipulation of matter at the scale of the nanometer (one billionth of a meter) – but possibly diversionary images of our techno-future.

The first and greatest impact of nano-scale technologies may come with the merger of nanotech and biotech – a newly recognized discipline called *nanobiotechnology*. While Gray Goo has grabbed the headlines, self-replicating nanobots are not yet possible. The more likely future scenario is that the merger of living and non-living matter will result in hybrid organisms and products that end up behaving in unpredictable and uncontrollable ways – get ready for "Green Goo!"

***Impact*:** Roughly one-fifth (21%) of nanotech businesses in the USA are currently focusing on nanobiotechnology for the development of pharmaceutical products, drug delivery systems and other healthcare-related products.[1] The US National Science Foundation predicts that the market for nano-scale products will reach $1 trillion per annum by 2015. As with biotech before it, nanotech is also expected to have a major impact on food and agriculture.

***Policies*:** No single intergovernmental body is charged with monitoring and regulating nanotechnology. There are no internationally accepted scientific standards governing laboratory research or the introduction of nano-scale products or materials. Some national governments (Germany and the USA, for example) are beginning to consider some aspects of nanotechnology regulation but no government is giving full consideration to the socioeconomic, environmental and health implications of this new industrial revolution.

***Fora*:** Informed international debate and assessment is urgently needed. Initiatives include: FAO's specialist committees should discuss the implications of nanotechnology for food and agriculture when they convene in Rome in March 2003. The Commission on Sustainable Development should review the work of FAO and consider additional initiatives during its New York session, April 28-May 9, 2003. The World Health Assembly, the governing body of the World Health Organization, should address health implications of nanotechnology when it meets in Geneva in May 2003. Ultimately, governments must begin negotiations to develop a legally binding International Convention for the Evaluation of New Technologies (ICENT).

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Introduction: Nanotech+Biotech

This year marks the 50th anniversary of the discovery of the double-helix – the structure of the DNA molecule and the catalyst for the biotechnology revolution. Also in the 1950s, physicist Richard Feynman theorized that it would be possible to work "at the bottom" – to manipulate atoms and molecules in a controlled and precise way. Today, our capacity to manipulate matter is moving from genes to atoms. Nanotechnology refers to the manipulation of atoms and molecules to create new products. ETC Group prefers the term "Atomtechnology," not only because it is more descriptive, but also because nanotechnology implies that the manipulation of matter will stop at the level of atoms and molecules – measured in nanometers. Atomtech refers to a spectrum of new technologies that operate at the nano-scale *and below* – that is, the manipulation of atoms, molecules and sub-atomic particles to create new products.

At the nano-scale, where objects are measured in billionths of meters, the distinction between living and non-living blurs. DNA is just another molecule, composed of atoms of carbon, hydrogen, oxygen, nitrogen and phosphorous – chemical elements of the Periodic Table – that are bonded in a particular way and can be artificially synthesized.[2] The raw materials for Atomtechnology are the chemical elements of the Periodic Table, the building blocks of all matter. Working at the nano-scale, scientists seek to control the elements of the Periodic Table in the way that a painter controls a palette of pigments. The goal is to create new materials and modify existing ones.

Size can change everything. At the nano-scale, the behavior of individual atoms is governed by quantum physics. Although the chemical composition of materials remains unchanged, nano-scale particles often exhibit very different and unexpected properties. Fundamental manufacturing characteristics such as colour, strength, electrical conductivity, melting point – the properties that we usually consider constant for a given material – can all change at the nano-scale.

Taking advantage of quantum physics, nanotech companies are engineering novel materials that may have entirely new properties never before identified in nature. Today, an estimated 140 companies are producing nanoparticles in powders, sprays and coatings to manufacture products such as scratchproof eyeglasses, crack-resistant paints, transparent sunscreens, stain-repellant fabrics, self-cleaning windows and more. The world market for nanoparticles is projected to rise 13% per annum, exceeding US$900 million in 2005.[3]

But designer nanoparticles are only the beginning. Some nano-enthusiasts look eagerly to a future when "nanobots" (nano-scale robots) become the world's workhorses. "Molecular nanotechnology" or "molecular manufacture" refers to a future stage of nanotechnology involving atom-by-atom construction to build macro-scale products. The idea is that armies of invisible, self-replicating nanobots (sometimes called assemblers and replicators) could build everything – from hamburgers to bicycles to buildings. A lively debate revolves around the extent to which molecular manufacturing will be possible – but scientists are already taking steps in that direction.[4]

Gray Goo:

Gray Goo refers to the obliteration of life that could result from the accidental and uncontrollable spread of self-replicating nanobots. The term was coined by K. Eric Drexler in the mid-1980s. Bill Joy, Chief Scientist at Sun MicroSystems, took Drexler's apocalyptic vision of nanotechnology run amok to a wider public.[5]

Drexler provides a vivid example of how quickly Gray Goo could devastate the planet, beginning with one rogue replicator. "If the first replicator could assemble a copy of itself in one thousand seconds, the two replicators could then build two more in the next thousand seconds, the four build another four, and the eight build another eight. At the end of ten hours, there are not thirty-six new replicators, but over 68 billion. In less than a day, they would weigh a ton; in less than two days, they would outweigh the Earth; in another four hours, they would exceed the mass of the Sun and all the planets combined."[6]

To avoid a Gray Goo apocalypse, Drexler and his Foresight Institute, a non-profit organization whose purpose is to prepare society for the era of molecular nanotechnology (MNT), have established guidelines for developing "safe" MNT devices. Foresight recommends that nano-devices be constructed in such a way that they are dependent on "a single artificial fuel source or artificial 'vitamins' that doesn't exist in any natural environment."[7] Foresight also suggests that scientists program "terminator" dates into their atomic creations…and update their computer virus-protection software regularly?

Most nanotech industry representatives have dismissed the possibility of self-replicating nanobots and pooh-pooh the Gray Goo theory. The few who do talk about the need for regulation believe that the benefits of nanotech outweigh the risks and call for industry self-regulation.[8]

The Gray Goo theory is plausible, but are mechanical, self-replicating nanobots really the road the nanotech industry will travel?

Buccolic Biotech: The biotech industry provides an important history lesson. Back in the early days, biotech enthusiasts promised durable disease resistance in plants, drought tolerance and self-fertilizing crops. But when the agbiotech companies marketed their first commercial genetically modified (GM) products in the mid 1990s, farmers were sold herbicide-tolerant plant varieties – GM seeds able to survive a toxic shower of corporate chemicals. The agrochemical industry recognized that it is easier and cheaper to adapt plants to chemicals than to adapt chemicals to plants. By contrast, the money involved in getting a new chemical through the regulatory maze runs into the hundreds of millions.

More recently, the biotech industry has figured out that GM crops could be cheaper, more efficient "living factories" for producing therapeutic proteins, vaccines and plastics than building costly manufacturing facilities. Companies are already testing "pharma crops" at hundreds of secret, experimental sites in the United States. While pharma crops may be cheaper and more efficient, industry is plagued by a persistent problem: living modified organisms are difficult to contain or control. Most recently, Texas-based biotech company ProdiGene was fined $250,000 in December 2002 when the US Department of Agriculture discovered that stalks of the company's pharma corn, engineered to produce a pig vaccine, had contaminated 500,000 bushels of soybeans.[9]

Atom & Eve in the Garden of Green Goo?

Atom & Eve: The nanotech industry seems to be following the biotech industry's strategy. Why construct self-replicating mechanical robots (by any standards an extraordinarily difficult task) when self-replicating materials are cheaply available all around? Why not replace machines with life instead of the other way around? Nanotech researchers are increasingly turning to the biomolecular world for both inspiration and raw materials. Nature's machinery may ultimately provide the avenue for atomic construction technology, precisely because living organisms are already capable of self-assembly and because they are ready-made, self-replicating machines. This is *nanobiotechnolgy* – manipulations at the nano-scale that seek to bring Atom (nano) & Eve (bio) together, to allow non-living matter and living matter to become compatible and in some cases interchangeable. But will the nanobiotech industry find itself battling out-of-control bio-nanobots in the same way that the biotech industry has come up against leaky genes? Will today's genetic pollution become tomorrow's "Green Goo?"

"The question now is not whether it is possible to produce hybrid living/nonliving devices but what is the best strategy for accelerating its development." **– Carlo D. Montemagno[10]**

Mergers and Acquisitions: When the living and non-living nano-realms merge in nanobiotechnology, it will happen on a two-way street. Biological material will be extracted and manipulated to perform machine functions and to make possible hybrid biological/nonbiological materials. Just as we used animal products in our early machines (e.g., leather straps or sheep stomachs), we will now adopt bits of viruses and bacteria into our nanomachines. Conversely, non-biological material will be used within living organisms to perform biological functions. Reconfiguring life to work in the service of machines (or as machines) makes economic and technological sense. "Life," after all, "is cheap" and, at the level of atoms and molecules, it doesn't look all that different from non-life. At the nano-scale, writes Alexandra Stikeman in *Technology Review*, "the distinction between biological and nonbiological materials often blurs."[11] The concepts of *living* and *non-living* are equally difficult to differentiate in the nanoworld.

Researchers are hoping to blend the best of both worlds by exploiting the material compatibility of atoms and molecules at the nano-scale. They seek to combine the capabilities of nonbiological material (such as electrical conductivity, for example) with the capabilities of certain kinds of biological material (self-assembly, self-repair and adaptability, for example).[12] At the macro-scale, researchers are already harnessing biological organisms for miniaturized industrial functions. For example, researchers at Tokyo University are remote-controlling cockroaches that have been surgically implanted with microchips. The goal is to use the insects for surveillance or to search for disaster victims. Recent examples of nanobiotechnology include:

- ***Hybrid Materials:*** Scientists are developing self-cleaning plastics with built-in enzymes that are designed to attack dirt on contact.[13] In the same vein, researchers are considering the prospect of an airplane wing fortified with carbon nanotubes stuffed with proteins. (Nanotubes are molecules of pure carbon that are 100 times stronger than steel and six times lighter.) If the airplane wing cracks (and the tubes along with it), the theory goes, fractured nanotubes would release the proteins, which will act as an adhesive – repairing the cracked wing and protracting its life span. Other scientists, using DNA as "scaffolding" to assemble conductive nonbiological materials for the development of ultrafast computer circuitry, are pioneering a new field of bioelectronics.[14]

Should we be thinking about the General Motors assembly line or the interior of a cell of E. coli? – **George M. Whitesides, Harvard University chemist[15]**

- ***Proteins Working Overtime:*** Proteins, the smallest class of biological machines, are proving to be flexible enough to participate in all kinds of extracurricular activities. A team of researchers at Rice University has been experimenting with F-actin, a protein resembling a long, thin fiber, which provides a cell's structural support and controls its shape and movement.[16] Proteins like F-actin allow the transportation of electricity along their length. The researchers hope these proteins can one day be used as biosensors – acting like electrically conductive nanowires. Protein nanowires could replace silicon nanowires, which have been used as biosensors but are more expensive to make and would seem to have a greater environmental impact than protein nanowires.

- ***Cell Power!*** A more complex working nanomachine with a biological engine has already been built by Carlo Montemagno (now at the University of California at Los Angeles). Montemagno's team extracted a rotary motor protein from a bacterial cell and connected it to a "nanopropeller" – a metallic cylinder 750 nm long and 150 nm wide. The biomolecular motor was powered by the bacteria's *adenosine triphosphate* (known as ATP – the source of chemical energy in cells) and was able to rotate the nanopropeller at an average speed of eight revolutions per second.[17] In October 2002, the team of researchers announced that by adding a chemical group to the protein motor, they have been able to switch the nanomachine on and off at will.[18]

- ***Molecular Carpentry:*** The motto of NanoFrames, a self-classified "biotechnology" company based in Boston, is "Harnessing nature to transform matter."[19] That motto is also a concise description of how Atom & Eve works. NanoFrames uses protein "subunits" to serve as basic building blocks (derived from the tail fibers of a common virus called Bacteriophage T4). These subunits are joined to each other or to other materials by means of self-assembly to produce larger structures. NanoFrames calls their method of manufacture "biomimetic carpentry," but that label, while wonderfully figurative, comes up short. Using protein building blocks to take advantage of their ability to self-assemble is more than imitating the biological realm (*mimesis* is Greek and means *imitation*). It's not just turning to biology for design inspiration – it is transforming biology into an industrial labor force.

- ***DNA Motors:*** Using a different kind of module – DNA – but similar logic, scientists are creating other kinds of complex devices from simple structures. In August 2000, researchers at Bell Labs (the R&D branch of Lucent Technologies) announced that they, along with scientists from the University of Oxford, had created the first DNA motors.[20] Taking advantage of the way pieces of DNA will lock together in only one particular way and their ability to self-assemble, researchers created a device resembling tweezers from two DNA strands. The tweezers remain open until "fuel" is added, which closes the tweezers. The fuel is simply another strand of DNA of a different sequence that allows it to latch on to the device and close it. Physicist Bernard Yurke of Bell Labs sees the DNA motor leading to "a test-tube technology that assembles complex structures, such as electronic circuits, through the orderly addition of molecules."[21]

- ***Living Plastic:*** Materials science researchers around the world are trying to perfect the manufacture of new kinds of plastics, produced by biosynthesis instead of chemical synthesis: the new materials are "grown" by bacteria rather than mixed in beakers by chemists in labs. These materials have advantages over chemically synthesized polymers because they are biocompatible and may be used in medical applications. Further, they may lead to the development of plastics from non-petrochemical sources, possibly revolutionizing a major multinational industry.[22] In one example, *E. coli* was genetically engineered – three genes from two different bacteria were introduced into the *E. coli*– so that it was able to produce an enzyme that made possible the polymerization reaction. In other words, a common bacteria, *E. coli*, was genetically manipulated so that it could serve as a plastics factory.[23]

Merging the living and non-living realms in the other direction – that is, incorporating non-living matter into living organisms to perform biological functions – is more familiar to us (e.g., pacemakers, artificial joints), but presents particular challenges at the nano-scale. Because nanomaterials are, in most cases, foreign to biology, they must be manipulated to make them biocompatible, to make them behave properly in their new environment.

- ***Olympic Nano:*** Researcher Robert Freitas is developing an artificial red blood cell that is able to deliver 236 times more oxygen to tissues than natural red blood cells.[24] The artificial cell, called a "respirocyte," measures one micron (1000 nanometers) in diameter and has a nanocomputer on board, which can be reprogrammed remotely via external acoustic signals. Freitas predicts his device will be used to treat anemia and lung disorders, but may also enhance human performance in the physically demanding arenas of sport and warfare. Freitas states that the effectiveness of the artificial cells will critically depend on their "mechanical reliability in the face of unusual environmental challenges" and on their biocompatibility. Among the risks, considered rare but real, Freitas lists overheating, explosion and "loss of physical integrity."

- ***Remote Control DNA:*** Researchers at MIT, led by physicist Joseph Jacobson and biomedical engineer Shuguang Zhang, have developed a way to control the behavior of individual molecules in a crowd of molecules.[25] They affixed gold nanoparticles (1.4 nm in diameter) to certain strands of DNA. When the gold-plated DNA is exposed to a magnetic field, the strands break apart; when the magnetic field is removed, the strands re-form immediately: the researchers have effectively developed a switch that will allow them to turn genes on and off. The goal is to speed up drug development, allowing pharmaceutical researchers to simulate the effects of a drug that also turns certain genes on or off. The MIT lab has recently licensed the technology to a biotech startup, engeneOS, which intends to "evolve detection and measurement *in vitro* into monitoring and manipulation at the molecular scale in cells and in vivo."[26] In other words, they intend to move these biodevices out of the test tube and into living bodies.

Nanobiotechnology: What are the Implications?

Green Goo: Human-made nanomachines that are powered by materials taken from living cells are a reality today. It won't be long before more and more of the cells' working parts are drafted into the service of human-made nanomachines. As the merging of living-nano and non-living nano becomes more common, the idea of *self-replicating* nanomachines seems less and less like a "futurist's daydream." In his dismissal of the possibility of molecular manufacture, Harvard University chemist

George Whitesides states that "it would be a staggering accomplishment to mimic the simplest living cell."[27] But we may not have to "reinvent the wheel" before human-made molecular creations are possible; we can just borrow it. Whitesides believes the most dangerous threat to the environment is not Gray Goo, but "self-catalyzing reactions," that is, chemical reactions that speed up and take place on their own, without the input of a chemist in a lab.[28] It is here – where natural nanomachines merge with mechanical nanomachines – that the Green Goo theory resonates strongest. The biotech industry has been unable to control or contain the unwanted escape of genetically modified organisms. Will the nanotech industry be better able to control atomically modified organisms? Nanobiotechnology will create both living and non-living hybrids previously unknown on earth. Will a newly-manufactured virus retrofitted with nano-hardware evolve and become problematic? The environmental and health implications of such new creations are unknown.

Six Degrees of Humanity: Can societies that have not yet come to grips with the nature of being human soldier on to construct partially-human, semi-human or super-human cyborgs?

Natural Born Killers: As the merging of living cells and human-made nanomachines develops, so will the sophistication of biological and chemical weaponry. These bio-mechanical hybrids will be more invasive, harder to detect and virtually impossible to combat.

Gray Governance: A 1999 study by Ernst & Young predicted that by 2010, there will be 10,000 connected microsensors for every person on the planet.[29] Nanosensors will undoubtedly surpass these numbers. What happens when super-smart machines and unlimited surveillance capacity get in the hands of police or military or governing elites? These technologies will pose a major threat to democracy and dissent and fundamental human rights. The powerfully invasive and literally invisible qualities of nano-scale sensors and devices become, in the wrong hands, extremely powerful tools for repression.

Wanted: A Molecular Recipe for Manufacturing Life

In November 2002, the outspoken gene scientist J. Craig Venter and Nobel Laureate Hamilton Smith announced that they were recipients of a $3 million grant from the US Energy Department to create a new, "minimalist" life form in the laboratory – a single-celled, partially human-made organism.[30] The goal is to learn how few genes are needed for the simplest bacterium to survive and reproduce. "We are wondering if we can come up with a molecular definition of life," Venter told the *Washington Post*.[31]

The researchers will begin with *Mycoplasma genitalium*, a simple microbe that lives in the genital tracts of people. After removing all genetic material from the organism, the researchers will synthesize an artificial chromosome and insert it into the "empty" cell. The longer-term goal is to manufacture a designer bacterium that will perform human-directed functions, such as a microbe that can absorb and store carbon dioxide from power plant emissions.

In essence, the mixing and matching of basic chemicals – synthesizing DNA to create a brand-new life form – is a grand experiment in nanobiotechnology. Will it also bring us Green Goo?

There are concerns that a partially human-made organism will provide the scientific groundwork for a new generation of biological weapons. Ironically, Venter abandoned his earlier quest to construct the world's first simple artificial life form in 1999 because he believed that the risk of creating a template for new biological weaponry was too great.[32] This time, Venter asserts, "We may not disclose all the details that would teach somebody else how to do this."[33]

Toward a Double-Green Goo Revolution?

Not for the first time, some scientists are predicting a “double-green” revolution. This time they say that nanotech will both improve the environment and contribute to human well-being – especially in the sectors of food and pharmaceuticals. (Civil society organizations with a history in biotech will experience an immediate déjà vu when they hear these claims.)

Slow Food Movement: Merging nanotech with biotech has enormous implications for food, agriculture and medicine. Some scientists dream of a world in which nanotech will allow our foods to assemble themselves from basic elements to become the entrée of the day.[34] No need to waste time planting and harvesting crops or fattening up livestock. No need for land – or farmers – at all. Just slip a polymer plate in the nanowave and out pops the family feast. It is, of course, theoretically possible to build a Big Mac or a Mac Apple or even the Big Apple atom-by-atom. But, at the current rate of construction, dinner would be late. In fact, nano food construction would bring a whole new dimension to the Slow Food Movement. Dinner won’t be ready until sometime after hell freezes over!

But if nanobiotechnology can't mash the potatoes just yet, there is still a great deal that these two converging technologies can accomplish within the life sciences…

Green Goo Giants: Although not always defined as nanotechnology, the Gene Giants and multinational food processors are either tracking nanotech or are actively engaged in developing the technologies. In a fall 2000 interview, Monsanto's then-CEO, Robert Shapiro, commented on the most promising emerging technologies, “…there are three, although I have a feeling that, under some future unified theory, they will turn out to be just one. The first is, of course, information technology… The second is biotechnology… And the third is nanotechnology.”[35]

Jozef Kokini, Director of Rutgers' Center for Advanced Food Technology, summarizes agribusiness’s interest in nano-scale technologies, "In our opinion, this is one technology that will have profound implications for the food industry, even though they're not very clear to a lot of people."[36]

"In our opinion, this is one technology that will have profound implications for the food industry, even though they're not very clear to a lot of people." **Jozef Kokini, Director of Rutgers' Center for Advanced Food Technology**

Special “K”: Kraft Foods may be more clear-sighted. In 1999, the $34 billion Philip-Morris subsidiary established the industry’s first nanotechnology food laboratory. In 2000, Kraft launched the NanoteK consortium, enveloping fifteen universities and public research labs, bent on basic research in food technology.[37] NanoteK is a heady broth of molecular chemists, engineers and physicists. Consortium participants include Harvard, Connecticut, and Nebraska universities, Chicago-based Argonne laboratories and the Los Alamos Lab famed for their role in developing America’s nuclear capacity. But NanoteK is not a US preserve. Much of the intellectual might comes from the Spanish universities of Seville and Málaga and from Uppsala University in Sweden. The venture may already be bearing fruit.

Smart Drinks: Kraft's first nano consumable may be a nano-capsule beverage.[38] Nanoparticles will encapsulate specific flavors, colours or nutritional elements that can be activated by zapping the solution with the appropriate radio frequency. Grocery stores and vending machines would sell a colourless, tasteless bottled fluid that customers could take home, zap, and transform into their beverage of choice. Microwave frequencies would activate the selected nano-capsules, effectively turning water into wine – or coffee – or single-malt scotch. Since the same mechanism could be used to release highly-concentrated drugs, the same bottled fluid might offer the Alka-Seltzer chasers for the scotch. Smart hangovers!

Smart Foods: Another innovation showing commercial potential is the addition of colour changing agents on food (or packaging), to alert the processor or the consumer to unsafe food.[39] Using “electronic tongue” technology, sensors that can detect chemicals at parts per trillion, the industry hopes to develop meat packaging that would change colour in the presence of harmful pathogens.[40] Food poisoning is already a major health risk and product recalls cause giant headaches for industry. Given the heightened concerns over bioterrorism, this is a nano-product with enormous commercial potential.

Out-of-Sight, Out-of-Mind?

Ready or not, nanotech is on its way. While much of the world has been mesmerized by G3 mobile phones and GM foods, the nanotech revolution is evolving quietly beneath the radar screen of government regulators and below the trip wires of life itself.

Because nano-scale technologies can be applied to virtually every industrial sector, no regulatory body is taking the lead. And because many of its products are nano-sized versions of conventional compounds, regulatory scrutiny has been deemed unnecessary. So far, nano-scale technologies are out-of-sight and out-of-mind for most politicians, regulators and the public.

The hard questions have not been asked. Basic questions like what mischief can nanoparticles create floating around in our ecosystem, our food supply and in our bodies? What happens when human-made nanoparticles are small enough to slip past our immune systems and enter living cells? What might be the socioeconomic impacts of this new industrial revolution? Who will control it? Shouldn't governments apply the Precautionary Principle? What if self-replicating nanobots – whether mechanical or biological or hybrids – multiply uncontrollably?

The world's most powerful emerging technology, Atomtechnology is developing in an almost-total political and regulatory vacuum. Even following ETC Group's July report warning that new nano-scale particles could pose a significant environmental and health issue – and advising further that no regulatory mechanisms exist covering nanotech research, neither governments nor industry have moved seriously to address these issues.[41] Meetings held by the U.S. Environmental Protection Agency with the U.S. National Science Foundation this past August have not led to calls for broad public discourse or regulation. Such failures threaten democracy and fuel fears of environmental harm and gray governance control over nano-scale technologies. Civil society organizations are beginning to embrace nano-scale technologies as an issue that must be addressed.

At the international level, ETC Group believes that intergovernmental bodies should begin an evaluation of the societal impacts of nano-scale technologies immediately. Eight specific initiatives should lead to an informed international debate at the UN General Assembly.

- Researchers should immediately volunteer – or governments should impose – a moratorium on new nanoparticle laboratory research until agreement can be reached, within the scientific community, on appropriate safety protocols for this research. Draft protocols should be available for public and governmental consideration as soon as possible;
- The agricultural and food implications of Atomtechnology and nanobiotechnology should be discussed by the FAO committee on agriculture at its next meeting in March, 2003 in Rome;
- The health considerations related to Atomtechnology and nanobiotechnology should be discussed by the WHO's World Health Assembly when it convenes in Geneva in May, 2003;
- The Commission of the European Union should bring forth a directive to properly address the social and environmental risks of nanotechnology, based on the precautionary principle;
- The International Labor Organization (ILO) should evaluate the socioeconomic impact of new nanotechnologies during the next meeting of its governing body;
- The technology division of the United Nations' Conference on Trade and Development (UNCTAD) should undertake an immediate evaluation of the trade and development implications/opportunities of Atomtechnology for developing countries;
- At its upcoming session in New York beginning the end of April, the UN Commission on Sustainable Development (CSD) should address the societal implications of nano-scale technologies;
- Based on the recommendations of the specialized agencies of the United Nations and the CSD, the UN General Assembly should launch the process of developing a legally binding International Convention on the Evaluation of New Technologies (ICENT).

[1] The NanoBusiness Alliance, “2001 Business of Nanotechnology Survey,” p. 12.
[2] The Periodic Table is a list of all known chemical elements, approximately 115 at present.
[3] Business Wire Inc., “Altair Nanotechnologies Awarded Patent for its Nano-sized Titanium Dioxide,” September 4, 2002. The estimate is based on market research conducted by Business Communications Co., Inc.
[4] For example, researchers at the Massachusetts Institute of Technology, have developed NanoWalkers – three-legged robots the size of a thumb. NanoWalkers are micro-robots, not nano-scale, but they are equipped with computers and atomic force microscopes that allow them to assemble structures on the molecular scale. For more information, see: ETC Group News Release, “Nanotech Takes a Giant Step Down!” March 6, 2002. Available on the Internet: www.etcgroup.org
[5] Bill Joy, “Why the Future Doesn’t Need Us, *Wired*, April, 2000.
[6] K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology*, originally published by Anchor Books, 1986, from the PDF available on the Internet: www.foresight.org, p. 216.
[7] The Foresight Institute’s Guidelines for Nanotech Development are available on the Internet: www.foresight.org/guidelines/current.html.
[8] For example, the Pacific Research Institute, promoters of “individual liberty through free markets,” released a study in November 2002 that calls for “a regime of modest regulation, civilian research and an emphasis on self-regulation and responsible, professional culture.” For more information, see: http://www.pacificresearch.org/press/rel/2002/pr_02-11-20.html The Center for Responsible Nanotechnology, (CRN), also an avid proponent of nanotechnology, is a new organization that conducts research and education about molecular nanotechnology. CRN believes that advanced, self-replicating nanotechnology is so powerful and dangerous that it could “raise the specter of catastrophic misuse including gray goo.” But CRN believes molecular nanotechnology is inevitable and can be used safely. According to CRN, “Well-informed policy must be set, and administrative institutions carefully designed and established, before molecular manufacturing is developed.” CRN was co-founded by Chris Phoenix, a senior associate at the Foresight Institute, and Mark Treder, Treasurer of the World Transhumanism Association. The website of the Center for Responsible Nanotechnology is: http://responsiblenanotechnology.org/links.htm
[9] Justin Gillis, “Drug-Making Crops' Potential Hindered by Fear of Tainted Food,” *Washington Post*, December 23, 2002, p. A1.
[10] Carlo Montemagno, “Nanomachines: A Roadmap for realizing the vision,” *Journal of Nanoparticle Research* 3, 2001, p. 3.
[11] Alexandra Stikeman, “Nano Biomaterials: New Combinations provide the best of both worlds,” *Technology Review*, MIT, November 2002, p. 35.
[12] Ibid.
[13] Ibid.
[14] Ibid.
[15] George M. Whitesides, “The Once and Future Nanomachine,” *Scientific American*, September 2001, p. 79.
[16]http://www.ruf.rice.edu/~cben/ProteinNanowires.shtml.
[17] George M. Whitesides and J. Christopher Love, “The Art of Building Small,” *Scientific American*, September 2001, p. 47. The *Scientific American* article incorrectly stated that the propeller revolved eight times per minute. See Montemagno et al., “Powering an Inorganic Nanodevice with a Biomolecular Motor,” *Science*, vol. 290, 24 November 2000, pp. 1555-1557; available on the Internet: www.sciencemag.org.
[18] Philip Ball, “Switch turns microscopic motor on and off,” *Nature* on-line science update, October 30, 2002; available on the Internet: www.nature.com
[19] www.nanoframes.com
[20] Bell Labs News Release, available on the Internet: www.bell-labs.com/news/2000
[21] Ibid.
[22] A. Steinbüchel et al., “Biosynthesis of novel thermoplastic polythioesters by engineered *Escherichia coli*,” *Nature Materials*, vol. 1 no.4, December 2002, pp. 236-240.
[23] Yoshiharu Doi, “Unnatural biopolymers,” *Nature Materials*, vol. 1 no. 4, December 2002, p. 207.
[24] Robert A. Freitas, “A Mechanical Artificial Red Cell: Exploratory Design in Medical Nanotechnology; ” available on the Internet: http://www.foresight.org/Nanomedicine/Respirocytes.html.
[25] Alexandra Stikeman, “Nanobiotech Makes the Diagnosis,” *Technology Review*, May 2002, p. 66.
[26] engeneOS web site, http://www.engeneos.com/comfocus/index.asp.
[27] George Whitesides, “The Once and Future Nanomachine,” *Scientific American*, September 2001, p. 83.
[28] Ibid.
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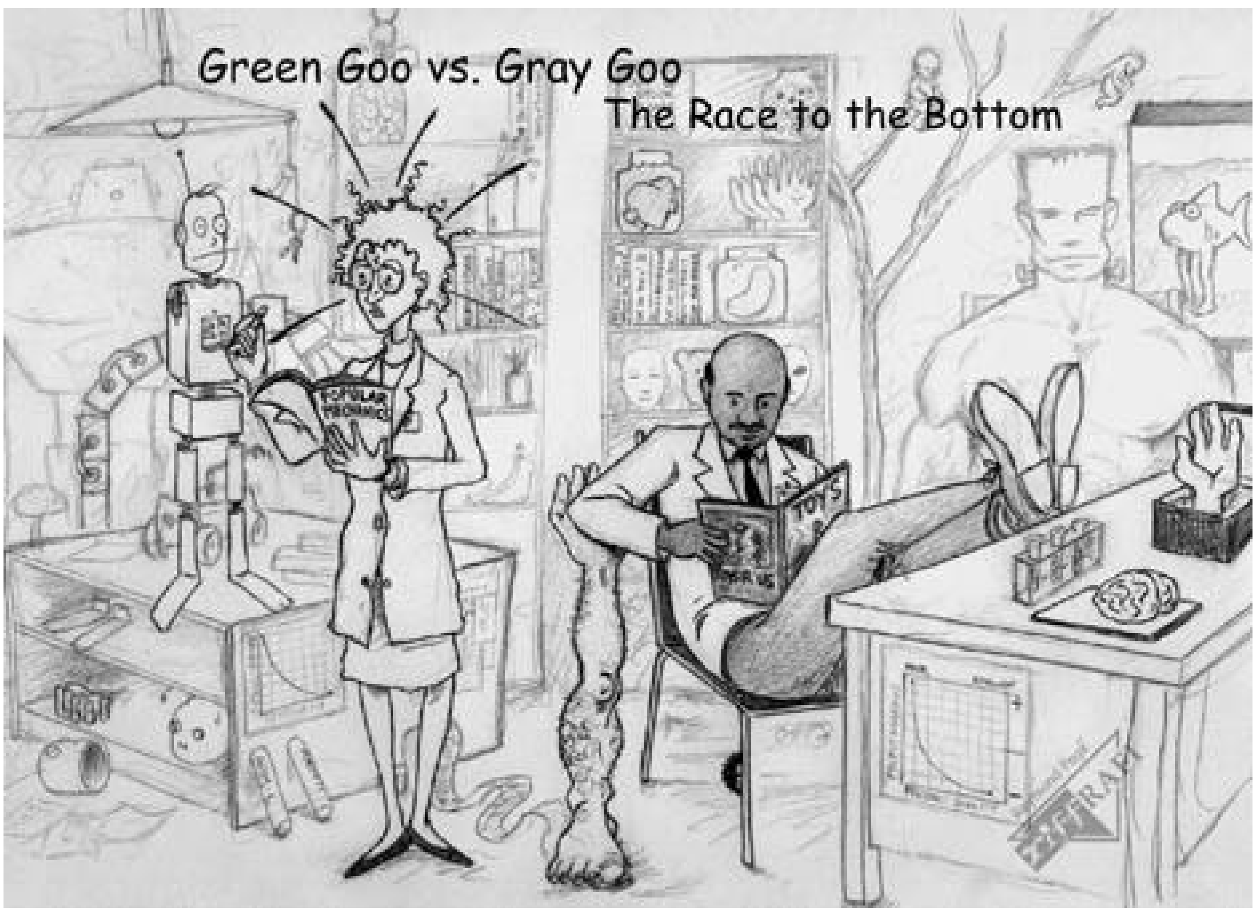
How might the new goo revolution play out? Will it be coloured gray or green or some other polychromatic combination? Will machines replace life or will life replace machines?

Who will Colour Your World?		
Gray Goo Theory ***Sorcerer's Apprentice***	**Gray Governance Theory** ***Orwell's 1984 –*** (20 Years Later)	**Green Goo Theory** ***Toys 'r Us***
Invisible self-replicating robots multiply uncontrollably until their thirst for raw materials (natural elements) and energy (or their products) consumes the world.	Super machines evolve to manage complex human and environmental systems and (eventually) either take over the world or fall into the hands of a corporate elite that rules omnipotently.	Scientists combine biological organisms and mechanical machines for industrial uses. The organisms continue to do what nature intended –they procreate –but they've been made more powerful by their boost from human technology.



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