# Oversight of Next Generation Nanotechnology

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# INTRODUCTION

For the first time in human history, we are close to being able to manipulate the basic forms of all things, living and inanimate, take them apart and put them together in almost any way the mind can imagine. The sophistication with which scientists are learning to engineer matter at the nanometer scale is giving us unprecedented mastery of a large part of our environment. The world of the future will be defined by how we use this mastery.

In contrast to the sweeping and dramatic possibilities of new technologies, the government agencies responsible for protecting the public from the adverse effects of these technologies seem worn and tattered. After almost 30 years of systematic neglect, the capability of federal health and safety regulatory agencies ranges from very weak to useless. The focus of regulatory reform in this period has mostly been on how to get around the existing regulatory structure rather than on how to improve it. The regulatory system was designed to deal with the technologies of the industrial age. A large gap exists between the capabilities of the regulatory system and the characteristics of what some are calling the next industrial revolution, and that gap is likely to widen as the new technologies advance.

Nanotechnology involves working at the scale of single atoms and molecules. The U.S. government defines nanotechnology as "the way discoveries made at the nanoscale are put to work" (www.nano.gov; accessed 9/19/08). The nanoscale is roughly 1–100 nanometers. For comparison, the paper on which this is printed is more than 100,000 nanometers thick. There are 25.4 million nanometers in an inch and 10 million nanometers in a centimeter.

Nanoscale materials often behave differently than materials with a larger structure do, even when the basic material (e.g., silver or carbon) is the same. Nanomaterials can have different chemical, physical, electrical and biological characteristics. For example, an aluminum can is perfectly safe, but nano-sized aluminum is highly explosive and can be used to make bombs.

The novel characteristics of nanomaterials mean that risk assessments developed for ordinary materials may be of limited use in deter- mining the health and environmental risks of the products of nanotechnology. While there are no documented cases of harm attributable specifically to a nanomaterial, a growing body of evidence points to the potential for unusual health and environmental risks (Oberdorster 2007; Maynard 2006). This is not surprising. Nanometer-scale particles can get to places in the environment and the human body that are inaccessible to larger particles, and as a consequence, unusual and unexpected exposures can occur. Nanomaterials have a much larger ratio of surface area to mass than ordinary materials do. It is at the surface of materials that biological and chemical reactions take place, and so we would expect nanomaterials to be more reactive than bulk materials. Novel exposure routes and greater reactivity can be useful at- tributes, but they also mean greater potential for health and environmental risk.

Oversight consists of obtaining risk in- formation and acting on it to prevent health and environmental damage. An underlying premise of this course is that adequate over- sight of nanotechnology is necessary not only to prevent damage but also to promote the development of the technology. The United States and Europe have learned that oversight and regulation are necessary for the proper functioning of markets and for public acceptance of new technologies.

The application of current oversight systems to current forms of nanotechnology has been analyzed for both the United States and Europe (see, for example, Davies 2006; Davies 2007; Royal Society and Royal Academy of Engineering 2004). The existing oversight systems in the United States have been found to be largely inadequate to deal with current nano- technology (Davies 2006, 2007, 2008; Taylor 2006, 2008; Felcher 2008; Breggin and Pendergrass 2007; Schultz and Barclay 2009). This course looks at future generations of nanotechnology. Not surprisingly, it finds that they will present even greater oversight challenges than the current technology. And nothing less than a completely new system will suffice to deal with the next generations of nanotechnology. The paper begins with an examination of the future of nanotechnology. It then analyzes the capacity of current oversight policies and authorities to deal with the anticipated technological developments. Concluding that the existing systems are inadequate, the major part of the paper is devoted to thinking about a more adequate oversight system for new technologies in general and for nano- technology in particular. Failure to think about new forms of oversight perpetuates the status quo and, in the long run, invites negative effects that could undermine the promise of the new century's technologies.

# 1. THE FUTURE OF NANOTECHNOLOGY

Predicting the future of any major technology is difficult. On the one hand, there of- ten is a tendency to underestimate the impact of a technology and the pace of its development. Nanotechnology development already is outpacing the predictions made when the NNI (National Nanotechnology Initiative) was created in 2000. At that time, the focus was on the impact nano might have in 20–30 years (Roco 2007). Now, the analysis firm Lux Research predicts that by 2015 nano will be incorporated in $3.1 trillion of manufactured goods worldwide (Lux Research 2008) and will account for 11 percent of manufacturing jobs globally (Lux Research 2006).

Alternatively, the promise of a technology and the pace of its development may be exaggerated. There are many examples of techno- logical advances that were predicted to be imminent but that had not materialized decades, or even centuries, later. A further complication is that a technology can develop in completely unanticipated directions and be applied in ways that no one envisaged.

This section begins by reviewing several analyses of nanotechnology's future and of cur- rent nanotechnology research. It then reviews applications of the research that are likely to occur in the next 10–20 years. It concludes by distilling the attributes that are likely to characterize future technologies in general and the next generation of nanotechnology specifically.

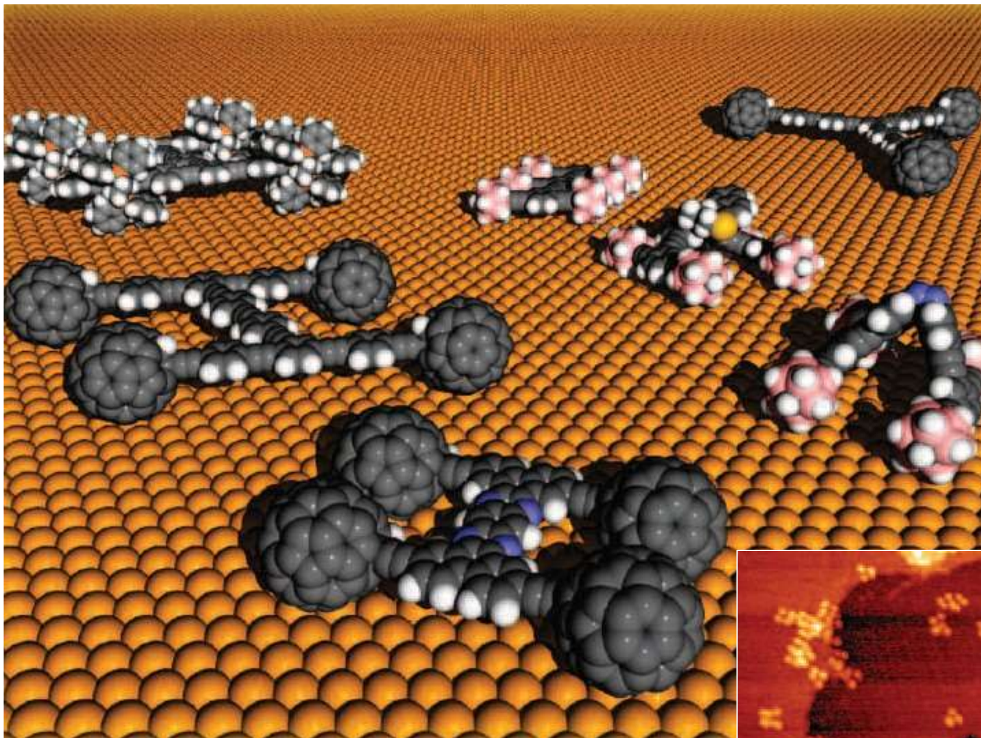
### NANOTECHBOLOGY RESEARCH AND DEVELOPMENT

The major attempts to analyze the future of nanotechnology have tried to categorize the types of research being conducted and/or the types of applications of the technology. The most straightforward categorization is that used by James Tour (2007) based on work in his Rice University laboratory. He categorizes nanotechnologies as passive, active or hybrid (i.e., technologies that are intermediate be- tween active and passive). Tour estimates the time it will take to commercialize each of these types as 0–5 years for passive nano- technologies, 15–50 years or more for active nano-technologies and 7–12 years for hybrids.

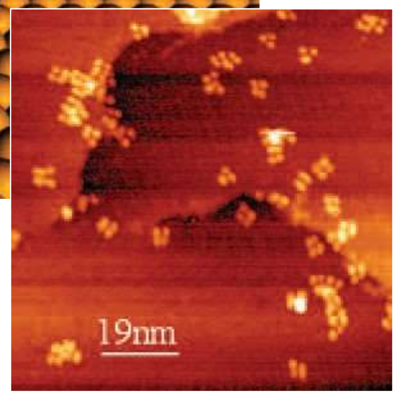
According to Tour, almost all the current applications of nano are passive, and most in- volve adding a nanomaterial to an ordinary material as a way of improving performance. For example, he notes that adding carbon nanotubes to rubber can greatly increase the toughness of the rubber without reducing its flexibility. Passive nanotechnology applications include using materials like carbon nanotubes, silver nanoparticles and porous nanomaterials—materials containing holes that are nano- meters in diameter. These applications use nanomaterials to add functionality to products by nature of their physical and chemical form, rather than by how they respond to their environment.

Tour defines an active nanotechnology as one where "the nano entity does something elaborate." He gives the example of a "nano- car," a unique nano-engineered molecule that can be used to physically move atoms from one place to another (see illustration on "Beyond Synthetic Chemistry)". One goal of next- generation nanotechnology is to imitate nature by designing systems and devices that construct things from the bottom up, (i.e., that make things atom by atom and molecule by molecule). This means

## BEYOND SYNTHETIC CHEMISTRY: An Example of Next Generation Nanotechnology



*Computer generated image of molecular "nano-cars".




**Scanning Tunneling Microscope image of "nano-car" molecules. The four carbon-60 molecules making up the wheels of each "nano-car" are easily visible.

Most scientists agree that we have only scratched the surface of the full range of molecules that could be made, if only we had better tools and a more complete understanding of how things work at the nanoscale. Building on advances in science and engineering, next generation nanotechnologies will enable the design and construction of increasingly complex molecules that rival those found in biology in terms of their sophistication. For example, Dr. James Tour and his research group at Rice University are engineering an innovative new class of molecules dubbed "nano-cars," that can move across a surface, and potentially ferry materials from one point to another at a nanometer scale.[1,2] Scientists are discovering that many biological processes depend on billions of molecules carrying out physical tasks, including ferrying materials around to construct, repair and fuel living cells. Mimicking these processes using artificial molecules—like the "nano-cars"—may open the door to constructing sophisticated new materials and products as diverse as medicines, electronic devices and building materials.

1. Sasaki, T., Osgood, A.J., Alemany, L.B., Kelly, K.F., and Tour, J.M. 2008. Synthesis of a Nano-car with an Angled Chassis. Toward Circling Movement. Organic Letters. 10(2), 229-232.

2. Vives, G. and J. M. Tour (2009). "Synthesis of Single-Molecule Nano-cars." *Acc. Chem. Res.* **42**(3): 473-487.

*Image courtesy of the American Chemical Society

**Image courtesy of the James M. Tour Group. http://www.jmtour.com/?page_id=33

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