6. Statements on Societal Implications

6.1 OVERVIEWS

National Nanotechnology Initiative

T. Kalil, White House

(Transcript from September 28, 2000)

Good morning, it's a pleasure for me to be here. I want to recognize the work that Mike Roco and the other members of the Nanoscience & Technology Working Group have been putting into developing this initiative. What I am going to do this morning is just give you an overview of the initiative, and then talk a little bit about some of the issues that I hope you will address today.

The national nanotechnology initiative was unveiled by President Clinton in a speech that he gave on science and technology policy in January of 2000. He called for an initiative with funding levels around 500 million dollars, and as he noted some of the research goals may take 10, 20, or even more years for us to realize. I think that's very important because I think there is a tendency in a new field when there is a lot of excitement to over-promise. For example, artificial intelligence that led to the famous AI winter, when people said that a strong artificial intelligence was just around the corner. I think it's important that people — even though there's a huge amount of enthusiasm about this area — continue to give the public a sense of how long it will take to make some of these breakthroughs. This gives you a sense for what was in the President's budget.

We estimate that in FY 2000 government agencies were investing around 270 million dollars in nanotechnology, and the President proposes to roughly double that. As you know, congress has not concluded the appropriations process right now. There are a number of areas where we are very concerned that congress has not provided full funding for this. For example, in the NSF budget, which is really the lead agency for the initiative, the congress has provided 125 million dollars for nanotechnology compared to our request of 217 million dollars. That's below the level that NSF was proposing to put into nanotechnology even if they didn't get any budget increase. NSF thought this area was important enough so that they were going to reallocate some of their base funding. We are particularly concerned about that, but we are also concerned about the lack of full funding for the initiative in DOE and NIST as well.

The initiative had five elements. The first was to increase support for fundamental research. The second was to pursue a set of grand challenges, which I am going to talk about later. The third was to support a series of centers of excellence, primarily university-based. The fourth was to increase support for research infrastructure. The fifth, what we are engaged in today, is to think about the ethical, economic, legal and social implications and also address the education and training of the nanotechnology workforce.

So what are some examples of some of these grand challenges? One was the ability to have really dramatic improvements in our ability to store and process information the way the President talked about this in the CalTech speech was the ability the equivalent of the Library of Congress in a device the size of a sugar cube; developing nanoengineered MRI contrast agents that might allow us to detect tumors that were a few cells in size as opposed to waiting until they are visible to the human eye; materials that were ten times stronger than steel at a fraction of the weight; doubling the energy efficiency of solar cells from 20% to 40% and something that was of great interest to NASA — the ability to have a continuous unmanned presence outside the solar system. So those were just a few examples of the types of grand challenges that we thought were possible.

Why now did the administration decide that this was an area that really deserved a great deal of attention and additional resources? First of all, I think there was a sense within the science and engineering community that this was an area that could have huge potential payoff and could be a technology that is every bit as significant as electricity or the development of the transistor or the Internet. It was also an area where, clearly, long-term, high risk research is needed which is where there is an important government role. For research that has a payoff that is longer than five years, it's very difficult for individual companies to justify to their shareholders making those sorts of investments.

This was an area that was also clearly interdisciplinary, where it's going to require collaboration between the biological/physical sciences and engineering, and we also saw it as a way of increasing support for the physical sciences and engineering. The reason that that's important is that, although biomedical research has enjoyed strong support on the Hill, support for the physical sciences and engineering has been stagnant. That's a real problem, both because these are important disciplines in their own right, and also because if we hope to make progress in biomedical research it will draw on innovations that are coming from physical sciences and engineering. A communications problem that we've had is that while there were members of Congress like speaker Gingrich that understood intuitively why it was a good idea to spend more money on biomedical research. We did not enjoy that depth and breadth of support for the physical sciences and engineering. So, increasing funding in this area was one way of addressing that major challenge in science policy.

There was a high level of enthusiasm in the community. This is not something that was a top-down initiative. I think it was really driven by the fact that the funding agencies were getting many more meritorious proposals than they were able to fund. This is a time when we are limited by dollars rather than ideas. NSF, for example, even after limiting proposals to two per campus was only able to fund 12% of the proposals that were coming in. We had some early promising results. The HP, UCLA and other breakthroughs in molecular electronics is a good example of that. This was an area that was important for multiple agency missions. We need nanotechnology if we are going to stay on the Moore's Law curve of improvements in price and performance in computers and electronics. Finally, particularly if we want to prepare the workforce that is going to be needed to capitalize on these new technologies, we need to increase support particularly in our universities. So that is, sort of in a nutshell, why the administration decided to make this area a priority and an area of emphasis in the President's 2001 budget.

Now, in thinking about the societal implications of nanotechnology, I think that we have to acknowledge from the outset that this is a very difficult exercise. We are at a stage where this is an inherently speculative exercise. As some of the speakers noted in their presentations, nanotechnology is sort of an umbrella term for a wide range of technologies. We've got differences of opinion about what the ultimate outcome of nanotechnology research is going to be, which is to be expected given that it is still a very young and undefined field. Even when we have technologies that are widely diffused, such as information technology, you don't have any consensus on what the impact is. So, does that mean that we should just sort of wash our hands and say let's not even bother thinking about it? I don't think that's the right answer either.

I think there a couple of directions that we can move down that may be fruitful — one is to identify particular applications of nanotechnology that are going to be broader societal objectives in areas like environment and health. Second, I think we can try to determine what lessons can be learned from studying the impacts of other technologies. For example, if we look at the literature on the impact of IT, a recurring theme of information technology and technology in general is something that is part of a broader socio-technical system. The reason that you can't predict what the impact is going to be is that it depends on the broader social, economic, and cultural context in which those technologies are embedded. I think that we need to start thinking of the potential risks and downsides. I think that although there are a number of points in Bill Joy's article that one could take issue with, I think it's difficult to deny his thesis that a lot of these technologies are going to end up increasing the destructive capability of small groups. Some of these technologies are not going to require Manhattan Project level of efforts in order to produce significant destructive capabilities. So, I think it behooves people to start thinking of those issues now as opposed to later. Then, I think you can engage in some scenario planning to say what are some different plausible scenarios. For example, what if we had 30 or 40 more years of Moore's Law style progress in storage and processing and what would that mean for our economy and our society? Even though this is an inherently difficult and speculative exercise, I don't think it's too early to start thinking about it.

I will conclude with a couple of thoughts. One is that I think we really need to reject this naïve technological determinism that I thought was best summed up by the slogan of the 1933 Chicago World's Fair, which is "science finds, industry applies, man conforms." I think that you encounter an attitude that technology is something that is totally out of control, and if it can happen it will happen. I think that's a dangerous attitude that we ought to reject. I think the other area that is particularly difficult in the area of nanotechnology is "keep an open mind but not so open that your brain falls out." I forget who said that, but I think one of the things that makes this discussion particularly difficult when you get into the thinking about 20 or 30 years out, is that different people have a different dividing line between keeping an open mind and allowing the brain to fall out. I think that's one of the things that will make this complex issue interesting. The third question I have is: there are certainly some people that believe that not only are we going to see continued change, which has been something that we are all familiar with, but that the rate of change itself is going to accelerate dramatically, so how seriously should we take this notion of some people in the field, particularly science fiction writers, that things are going to get very different and very weird over the next 20 to 40 years? So, with that I want to thank everyone for coming and participating in this workshop, because we really are going to need the best minds thinking and working in this issue. Thank you very much.

THE AGE OF TRANSITIONS

N. Gingrich, American Enterprise Institute

My perspective on the societal implications of nanoscience is as an historian, an amateur student of science and as an elected official with a long time in government. I have done an extensive amount of reading and talked to people all across America who have made or are on the edge of breakthroughs in science and technology. The newest, least understood, and most promising area of science, in my opinion is nano scale science and technology.

I'd like to try and put nanoscience in some kind of historical perspective, starting with the concept of an S-curve of technology (see Figure 6.1). (A more detailed version is the "Age of Transitions" at http://www.newt.org.)

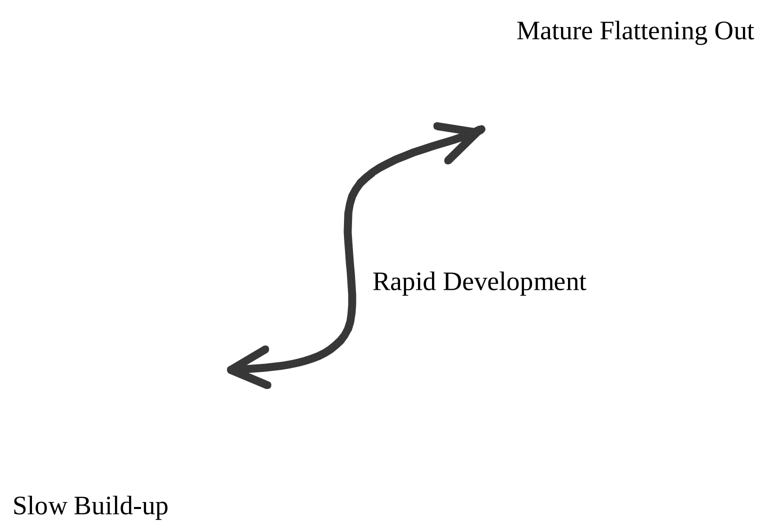

Figure 6.1. The concept of an S-curve of technology.

As a general rule breakthroughs start relatively slow; they build up momentum, they suddenly reach a period of catalytic change, they go up the curve of capability very, very rapidly and then as they mature they tend to level out.

The S-curve we have been experiencing, the revolution in computing and communications that has been dubbed the Information Age, began around 1965. It is the result of two developments — computing and communications.

Computing is a key element in this change and we are only one-fifth of the way into developing the computer revolution. To take one metric, according to Professor James Meindl, the chairman of the Georgia Tech Microelectronics Department, the first computer built with a transistor was “Tradic” in 1955, and it had only 800 transistors. The Pentium II chip has 7.5 million transistors. The Pentium III chip has 29 million transistors. In the next year or so an experimental chip will be built with one billion transistors. Within fifteen to twenty years there will be a chip with one trillion transistors. Graphing that scale of change, it is enormous and its implications are huge.

Yet focusing only on computer power understates the rate of change. Communications capabilities are going to continue to expand dramatically and that may have as big an impact as computing power on our society and economy. Today most homes get Internet access at 28,000 to 56,000 bits per second. Within a few years a combination of new technologies for compressing information (allowing you to get more done in a given capacity) with bigger capacity (fiber optic and cable) and entirely new approaches (such as satellite direct broadcast for the Internet) may move household access up to at least six million bits per second, and some believe we may reach the 110 million bits needed for uncompressed motion pictures. An amazing range of opportunities have and will continue to open up as our communications capabilities continue to improve and grow.

When you look at the distance we have traveled in relation to computing and communications capabilities and the distance scientists are predicting we will travel in the next 20 years, I believe that we are only one-fifth of the way along that S-curve (see Figure 6.2).

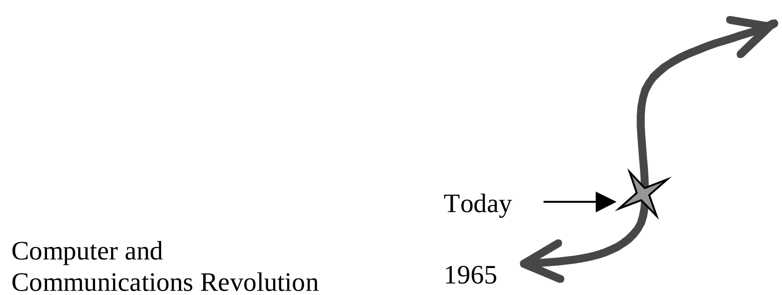

Figure 6.2. Present position on the S-curve of technology.

Even that understates the rate and scale of change because there is a second S-curve that is beginning to develop, overlapping with the current S-curve. The best description I have found of this second wave of change is the NASA AMES laboratory version. In their mission statement, they use a triangle with biology on one side, nanoscience or nanotechnology on the other side, and information, by which they mean supercomputing and above, at the bottom of the triangle. It is the interaction of those three that, I think, leads to an enormous wave of change, which creates the second S-curve (see Figure 6.3 and Figure 6.4).

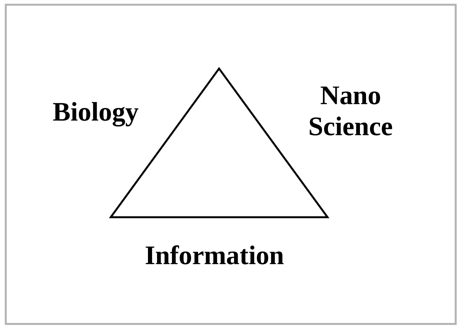

Figure 6.3.

So, looking out over the next 30 years, as these two S-curves continue to accelerate and continue to overlap, we are going to be impacted by two large, profound waves of change. It is the overlapping period we are just beginning to enter that I believe will be an Age of Transitions.

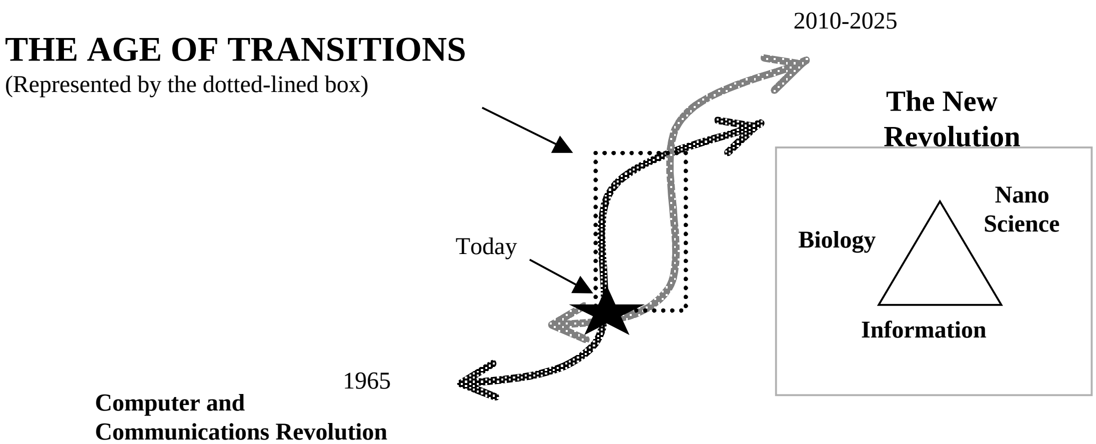

Figure 6.4. The age of transitions.

The age of transitions will be an ever-evolving set of discoveries, with the information world increasingly interacting with the physical world.

The topic of this conference is the societal implications of nanoscience. Discoveries involving nanoscience will be as dramatic and, I believe, even more important than the creation of the Internet. Let's consider the economic impact nanoscience may have our society. Bill Joy, co-founder and Chief Scientist of Sun Microsystems, has estimated that the combination of the information and physical world will create in this century a thousand trillion dollars worth of wealth. As a former lawmaker, I thought I was used to dealing in big sums. This is really big! In fact, it would be adding 100 U.S. economies to the world market.

The application of nanoscience into nanotechnology will introduce disruptive technologies into our lives and, therefore, into the economy. Large corporations have been very successful at improving a product or service they are already providing. While working to improve existing products, their new science will also create disruptive technologies. It is very hard for corporations to incorporate disruptive technologies. Clayton M. Christensen, in *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, describes case after case of new entrants dominating a field by creating technology that big firms ignored. These disruptive technologies were initially too slow or too poor in performance to react well to meet the needs of the customers. It was not that these big corporations were stupid or irrational; their customers initially looked at the new technology and said, "I don't want it." A new layer of customers then appeared to create a new market that embraced the disruptive technology and it eventually became the norm. Disk drives, hydraulic shovels, mini-mills are just a few examples of technologies once considered disruptive and studied by Christensen.

When more research in the area of nanoscience is done, you will not only have a disruption in scientific assumptions that lead to new discoveries, you will see the nanoscience being applied to new economic sectors in ways that cannot be anticipated.

The application of nanoscience into real marketable products will be much more rapid than we saw with the Internet or other revolutionary technologies. When computing began, we had a remarkably primitive venture capital entrepreneurial system. As nanoscience is translated into nanotechnology it will be entering a very aggressive, very well financed, very experienced entrepreneurial venture world, which will be hungrily looking for the next big deal. So the rate of translation into new startups and new markets should be orders of magnitude faster than it was for computing.

Let's turn for a moment away from placing nanoscience in the context of historical trends and look more at the uniqueness of the science itself. As a student of science, I am going to make some assertions. These may be corrected by my other conference attendees but, again, as a student, the implications of nanoscience strike me as profound. Nanoscience is the base of how the world operates. There may be many layers below the atom, but for practical purposes an atom is an excellent base element. Taking the information nanoscience is teaching us about atoms and their activity and applying it has dramatic implications. Take the environment for example. We can learn to grow products using less energy and with less waste by product. It may mean that if we use dramatically less energy, then the projections and assumptions of current environmental debates, like Kyoto, are totally obsolete. It certainly means in biology that as we get better nano instrumentation and research tools, and if our nanoscale observational capabilities continue to grow, our capacity to deal with the complexities of human biology are going to go up dramatically and may not even be only orders of magnitude, but a different world of capabilities. For example, I recently met with the NSF cognitive science group and learned that in brain wave scanning, we are still at the molecular level. The potential of nano-level brain wave scanning is a new frontier in mind science. The application towards improving our education techniques alone are enormous.

If we want to stay at the forefront economically and remain a world leader politically and militarily, I think we have an obligation to really look seriously at funding more nanoscience research. Although President Clinton deserves credit for creating the National Nanotechnology Initiative, the amount he requested barely scratches the surface of what we need to be spending. This is an extraordinary national security issue. America is certainly not the only country working on advancing the field of nanoscience. The Japanese are working on it. The Europeans are working on it. In a decade you are going to see the Indians and the Chinese with a very major effort in this area because it will become obvious that it is so profoundly important.

After a year and a half of talking with scientists around the country I reached the conclusion that we need to rethink from the ground up how we design our science budget. In fact, I want to introduce the idea of an opportunities-based science budget (longer explanation can be found at www.newt.org.) If without any comprehensive effort you have eight times as many applications as you can finance (which is what many agency directors have testified), talking about a six percent or nine percent increase is inadequate.

I believe that we are actually at the edge of an age of discovery that is vastly richer than anybody yet understands. When I was at MIT they were very excited by the fact that the human ear has a million moving parts. We couldn't have discovered that fifteen or twenty years ago. We still don't fully understand what it means. Dr. Francis Crick, co-discoverer of the structure of the DNA molecule, told me that, in his judgment, it would take a hundred years of work to finish out the human genome project's implications. Most Americans think it's almost done, and the newspaper says they are almost done with "X" so we think we should relax. I am beginning to believe just the opposite. We are at the opening of an age of discovery. We have a whole new wave of things about to happen. Therefore, what I want to propose is an opportunities-based science budget. We actually go out and say to all scientists: if you had the money, if you were not in an economically constrained environment — what is it that we could learn across the whole system from astronomy to physics to math to biology to chemistry. I think what you would find is that we would have lots of grand projects we can't even dream of today because we start with a relatively limited budget. Again, I would cite the international geophysical year as a model that changed geology decisively because it was a large enough model that we had the data on the right level.

I have sent a letter to the appropriation chairmen and Senator Lott and Speaker Hastert suggesting that the real number for NSF (letter found at www.newt.org) ought to be to catch up with NIH. Since 1994, we've increased the NIH budget 72% and the NSF budget 27% — that is in the long run profoundly wrong because if you don't invest in math, physics, chemistry, etc., if you don't invest in basic research, basic instrumentation, you will run out of the capability to do fresh biological work. When Harold Varmus was the Director of NIH, he even testified to this point in front of Congress. It is vital that we reassert the centrality of fundamental research in this country.

Finally, we cannot lead the world if we do not profoundly overhaul math and science education. This is a sleeping crisis of unbelievable proportions. If, in fact, the scale of change is as large as I just suggested, then in order to stay at the forefront we have to have a lot more 19-year-olds capable of doing math and science. We just don't have them, and the current system isn't producing them. This is a crisis that requires at least an Eisenhower-level kind of national security look at this — even if that means paying high-schoolers to take calculus. It is literally worth our thinking through any change we have to make in order to produce a nation in which enough people are capable of doing math and science. Nothing less will do.

TECHNOLOGICAL IMPLICATIONS OF NANOTECHNOLOGY: WHY THE FUTURE NEEDS US

J.A. Armstrong, IBM VP, Sci. & Tech. (ret.)

Introductory Remarks

I have been asked to talk about "the technological implications of nanotechnology." This is a tall order for at least two reasons. First, because the technological and societal implications of the major, present nanotechnologies, semiconductor and magnetic recording, are so vast that it would take a month of workshops to explore them. Second, the topic is a tall order regarding the *new* nanotechnologies because no one is sure what they will be and which will be most successful and therefore pervasive and capable of having significant impacts, both good and (possibly) adverse.

I find that the very term "nanotechnology" — although wonderfully suited to the description of a welcome and significant funding initiative — is at too high a level of abstraction for our purposes here today. Which "nanotechnology" are we supposed to be talking about? Surely not semiconductors and magnetic recording, except as historical examples and sources of valuable lessons.

Do we mean the new nanotechnologies that make use of the fabrication methods of traditional silicon technology but extend them by incorporating exotic new materials from the realms of biology, chemical sensing, and genetic engineering?

Or do we mean technologies based on chemical and materials-science methods that can produce tiny particles — such as nanotubes and wires — with remarkable properties despite the lack of lithographically defined spatial ordering?

Or, as is likely, some hybrid of the above? Or something altogether different that we will hear about during the course of the workshop?

The question "Which nanotechnology?" is important because the societal impacts (almost certainly overwhelmingly benign, but possibly occasionally adverse) depend very much on which technology is involved, and *even more soon which application is involved.*

In their wisdom, the progenitors of this workshop have left all these questions open, no doubt with the intention of ensuring a very stimulating and wide ranging discussion. So I am going to put forth a list of five questions of my own, and then proceed to answer, or at least to address them.

Questions

First question: *Why are we having this workshop at all?* When the Administration and Congress fund an NSF initiative to build a high energy physics detector, or a supercomputer, or an Engineering Research Center, we do not normally proceed to collective scrutiny of possible societal impacts. May it be that we have promised too much in the way of a nano revolution, and aroused unease in the community at large? Is there some message that goes *beyond* nanoscience and technology that we should be alert to? Are more and more areas of scientific research going to be funded with these precautionary measures attached?

Second question: *What can we learn from the examples of past technology developments and societal impacts* that will be helpful in thinking about the future of nano developments? There is, in my view, much to be gained from reflecting on the emergence of semiconductor technology as a major force shaping society. Not all of the coming nanotechnologies will share attributes of the semiconductor revolution, but some will.

Third question: *Can we say anything useful* a priori *about the impacts of the* ***manufacturing*** *of new nanotechnological devices as distinct from the societal impacts of the* ***applications*** *to which the new devices will be put*? This is a subset of the previous question, but easier to deal with in concrete terms.

Fourth question: *How is one to measure societal impacts anyway?* (a) What will count as benign and what as adverse? Recall Joseph Schumpeter's characterization of the genius of modern capitalism as "creative destruction." Much of that creative destruction has been enabled by the digital revolution that in turn was made possible by nanotechnology. In many cases, one man's benign impact is another man's adverse impact. (b) Can we use one or more of the emerging nanotechnologies as test-beds for determining so-called "societal returns?" For example, what is to be counted in the set of societal returns, as opposed to the private returns which will accrue to firms that bring the new technologies to market? It is certain that the list of what is to be counted as "private return" is very different from the list of what is to be counted as societal return. Indeed, some of what is counted as societal return is counted by the private sector as *investment*, not return. (c) And how are we to measure adverse impacts quantitatively? I am neither an economist nor social scientist, but I am interested in these matters and frustrated by what I perceive as a lack of clarity and transparency in discussions by specialists.

Fifth question: In view of the miserable track record in long range forecasting that has been run up by scientific and technical experts over the years, *why would anyone take seriously what we have to say about societal impacts decades into the future* of any of the emerging new nanotechnologies?

Responses

The remainder of my talk will deal as fully with these questions as can be done in twenty minutes! But the main points I will try to make are these:

- We can say many plausible things about the possible evolution of new nanotechnologies. But because of the great uncertainties that surround the future, no **particular** view or concern about future impacts can have **scientific** claim to be so certain that policy should seriously constrain scientific options now.
- The whole aim of our forethought and intellectual preparation and policymaking should be to ensure that we can flexibly respond to impacts as they appear on the horizon, no matter how different they may be from what we expected.
- And therefore, the Future Does Need Us, we who can be flexible and rational and respond to surprises and unintended consequences, as well as respond to wonderful new opportunities. (If you are worried, as some seem to be, about a robotic future full of nano mechanisms that don't need us, I suggest you rent a copy of Woody Allen's *Sleeper* from the video store, and restore your sense of balance!)

DON'T COUNT SOCIETY OUT: A RESPONSE TO BILL JOY

J.S. Brown, Xerox Palo Alto Research Center; P. Duguid, University of California, Berkeley

Summary

The April issue of *Wired* carried an article by Bill Joy, cofounder and chief scientist of Sun Microsystems, called "Why The Future Doesn't Need Us." The article argued that "our most powerful 21st-century technologies — robotics, genetic engineering, and nanotechnology — are threatening to make humans an endangered species." Here, we offer a response.

All of us need to worry about the concerns Joy raises. Technology is moving frighteningly fast. But much of the fear in Joy's article comes from a tendency among the digerati, when surveying technological change, to extrapolate from the steepest part of the curve or, in effect, to count in the order of 1, 2, 3, ... a million — or even infinity. You can see this in old predictions that a few years would take us from industrial nuclear power plants to domestic ones. And you can see it again in the short steps Joy takes from the possibility of replicating peptides to the imminent certainty of a robot society, or from the theory of nanotechnology to its practical implications.

This sort of counting is an example of what we call "tunnel vision." It excludes all the other factors that come into play as technologies develop. In particular, it excludes the social factors that always shape and redirect technology, making counting much harder. In making this argument, we are not arguing that there is therefore nothing to worry about. Far from it. The cause for worry is real. Instead, we are suggesting that — contrary to those who can only see disaster — something can be done. But what that something may be is very hard to see if tunnel vision cuts out all the forces in play except for the technological ones.

Our response asks that the social factors at work be factored in. Society and technology develop, we argue, in co-evolutionary steps, each profoundly affecting the other. When the social forces are left out of the picture, there seems nothing else to do but resign ourselves to wait for a future that doesn't need us. On the other hand, if the role of social forces in the co-evolutionary spiral is clear, then warnings like Joy's highlight the need to develop new social forms, new kinds of organization, and new formal and informal institutions to replace the slow, outmoded ones and to respond rapidly to rapid social change. It's at this level, we believe, that debate should be engaged.

Introduction

Whatever happened to the household nuclear power pack? The full-scale nuclear generator had barely left the drawing board before futurists predicted that every house would soon have a smaller version. From here, technoenthusiasts could see the end of power monopolies, the emergence of the "electronic cottage," the death of the city, and the long decline of the corporation. Pessimists and Luddites, of course, primarily foresaw localized nuclear meltdown and household nuclear weapons. Each side waited for Nirvana or Armageddon to roll by so it could triumphantly tell the other, "I told you so." They're still waiting.

Bill Joy's recent article "Why the Future Doesn't Need Us" (*Wired* 8.04) brings those old controversies to mind. In saying this, we do not want to underestimate the importance of Joy's much-cited article. No Luddite, Joy is an awe-inspiring technologist. So when he describes a technological juggernaut thundering towards society and worries that even those straight in its pathway are blindly cheering, all of us need to listen. Like the nuclear prognosticators, Joy can see the juggernaut clearly. Like them, too, he can't see any controls. Indeed, it's the absence of controls that makes his vision so scary. But it doesn't follow that the juggernaut is uncontrollable.

To understand why no controls are visible, readers should note the publication in which this article appears. For the best part of a decade, *Wired* has been an enjoyable cheerleader for the digital age. Its shift with Joy's article from cheering to warning marks an important moment in the digital *zeitgeis*t. Finally, many prognosticators, like investors, are coming to realize that rapid technological innovation can have a down side. And as with many investors, the tone in *Wired* has swung straight from wild euphoria to high anxiety — as if there were no middle ground. That the change in mood should be so extreme is not all that surprising. When they felt we were all being triumphantly carried along by technology, the digerati saw little need to look for the brake. So now they fear that, rather than being carried, we are instead standing smack in technology's path, and they don't seem to know where a brake might be found.

To see where one might lie, let's go back to the nuclear power pack. Innovation, the argument went, would make nuclear plants smaller and cheaper. These would soon shrink to household size. Then they would enter mass production and quickly become available to all. The argument still seems unavoidable — until you notice what's missing. The tight focus of this vision makes it almost impossible to see forces other than technology at work. Yet in the case of nuclear development, there were many other forces at work.

These included the environmental movement, anti-nuclear protests, concerned scientists, worried neighbors of Chernobyl and Three Mile Island, NIMBY responses to nuclear waste, government regulators, anti-proliferation treaties, and corporate-shareholder rebellions. Cumulatively, these forces slowed the nuclear juggernaut to a manageable crawl. Similar social forces are at work on modern technologies today. But because the digerati, like technoenthusiasts before them, look to the future through a narrow technological tunnel, they too have trouble bringing other forces into view.

The Tunnel Ahead

As an emblem of technological futurism, take the cover of Bill Gates's first book, *The Road Ahead.* This showed a smiling Gates standing before an empty blacktop stretching unproblematically into the future. There was the road. Gates pointed. We needed only to follow it. When the book appeared, *The Nation* magazine put an ad with this picture next to one for a Bruce Springsteen concert. In that, if memory serves, a world-weary Springsteen stood outside a tavern in some unidentified, industrial-age town. The tavern looked seedy. Traffic blocked the oily, rain-swept road. The guys outside the tavern probably weren't sober. And the women further down the road probably weren't waiting for buses. The contrast between the two ads reminded us how much easier it is to lay out the road ahead with confidence and plausibility if you only think about road and ignore all the messiness that people willfully bring to the picture.

Leaving people out of the picture and focusing on technology in splendid isolation, tunnel vision doesn't only lead to both exuberant and doom-and-gloom scenarios by the bucketful. It also leads to tunnel design — the design of "simple" technologies that are actually very difficult to use. So to escape both trite scenarios and bad design, we have to widen horizons and bring into view not just technological systems, but also social systems. Good designs look beyond the dazzling potential of the technology to social factors such as the limited patience of most users. Paying attention to the latter has, for example, allowed the Palm Pilot and Nintendo Gameboy to sweep aside more complex rivals. Their elegant simplicity has made them readily usable. And their usability has in turn created an important social support system. They are so widely used that now anyone having trouble using a Pilot or Gameboy rarely has to look far for a more experienced user to give advice.

As this small example suggests, technological and social systems shape each other. The same is true on a larger scale. Technologies, as gunpowder, the printing press, the railroad, the telegraph, and the Internet have shown, shape society in quite profound ways. But equally, social systems, in the form of government, the courts, formal and informal organizations, social movements, professional networks, local communities, market institutions, and so forth, shape, moderate, and redirect the raw power of technologies. The whole process might best be thought of as one of "co-evolution," with society and technology mutually shaping each other. In considering one, then, it's important to keep the other in mind. Given the crisp edges of technology and the fuzzy ones of society, it certainly isn't easy to grasp the two simultaneously. But grasp both you must, if you want to see where we are all going or design the means to get there.

Tidings of Discomfort?

This joint perspective allows a more sanguine look at the central concerns Bill Joy laid out in *Wired*: genetic engineering, nanotechnology, and robotics. Undoubtedly each deserves serious thought. But each should be viewed in the context of the social system in which it is inevitably embedded. That context provides, to return to our earlier metaphor, a glimpse of the brake and steering mechanisms on what otherwise would appear as an out-of-control juggernaut.

Genetic engineering presents the clearest example. Barely a year ago this seemed an unstoppable force. Major chemical and agricultural interests were barreling unstoppably along an open highway. In the past twelve months or so, however, road conditions have changed dramatically. Cargill has faced Third World protests against its patents. Monsanto has suspended research on sterile seeds. And champions of genetically modified foods, who once saw an unproblematic and lucrative future, are scurrying to counter consumer boycotts of their products. If, as some people fear, genetic engineering represents one of the horses of the Apocalypse, it is certainly no longer unbridled.

Erratic biotech stocks suggest that it’s now very hard to see beyond this immediate, sharp curve in what once looked like an open road. There’s no clear consensus — only a lot of name calling (Frankenfood! Luddites!). Almost certainly, those who support genetic modification will have to look beyond the labs and the technology if they want to advance. They need to address society directly — not just by labeling modified foods, but by educating people about the costs and the benefits. Of course, having ignored social concerns, proponents have made the people they need to educate profoundly suspicious and hostile. In consequence, they have made their road significantly more uphill.

Nanotechnology offers a rather different example of how the future can frighten us. For this, which involves engineering at a molecular level, both the promise and the threat seem unmeasurable. But they are unmeasurable for a good reason. The technology is still almost wholly on the drawing board. Two of its main proponents, Ralph Merkle and Eric Drexler, worked with us at Xerox PARC. They built powerful nano-CAD tools and then ran simulations of the resulting designs. The simulations showed definitively that nano devices are theoretically feasible. But theoretically feasible and practically feasible are two different things. And as yet, no-one has laid out in any detail a route from lab-based simulation to practical development.

So here the road ahead is unpredictable not because of an unexpected curve, but because the road itself still lacks a blueprint. In the absence of a plan, it’s certainly important to ask the right questions. Can nanotechnology actually fulfill its great potential in tasks ranging from data storage to pollution control? And can it do such things without itself getting out of control? But no one should worry too much about the road’s maintenance crew when the road itself has yet to be surveyed. If the lesson of genetic engineering means anything, however, even though useful nano-systems are probably decades away, planners would do well to consult and educate the public early on.

Worries about *robotics* suggest that here, too, the route has been added to our mapbooks long before the road itself has actually been built. Take for example the much-talked about "bots" — the software equivalent of robots, which search, communicate, negotiate, or act as agents on the Internet. They, it has been claimed, do many human tasks much better than humans and so indeed might come to replace us all. In fact, bots are useful because they are quite different from humans. They are good (and useful) for those tasks that humans do badly. They are often quite inept at tasks that humans do well — tasks that call for judgement, taste, discretion, initiative, or tacit understanding. So bots are probably better thought of as complementary systems, not rivals to humanity. Consequently, though they will undoubtedly get better at what they do, such development will not necessarily make bots more human. They are in effect being driven down a different road. Certainly, the possibility of a collision needs to be kept in mind. In particular, we need to know who will be held responsible when autonomous bots inadvertently cause collisions — as well they might. But we probably need not look for significant collisions around the next few bends.

Are more conventional robots — the villains of science fiction — any greater threat to society? We doubt it. PARC research on self-aware, reconfigurable polybots has pushed at new robotic frontiers. When these are combined with our MEMS (microelectical mechanical systems) research, they point the way to morphing robots whose ability to move and change shape will make them important for such things as search and rescue in conditions where humans cannot or dare not go. Nonetheless, for all their cutting-edge agility, these robots are a long way from making good free-form dancing partners. In particular, like all robots (but unlike good dancing partners), they lack true conversational skills. The chatty manner of C3-PO still lies well beyond machines. Indeed, what talking robots or computers do, though it may appear similar, is quite different from human talk. Talking machines travel routes designed specifically to avoid the full complexities of situated human language.

True, robots may still seem quite intelligent. Yet such intelligence is profoundly hampered by their inability to learn in any significant way. (This failing has apparently led Toyota, after heavy investment in robotics, to consider replacing robots with humans on many production lines.) And without learning, simple common sense will lie beyond robots for a long time to come. Indeed, despite years of startling advances and innumerable successes like the chess-playing Big Blue, computer science is still almost as far as it ever was from building a machine with the learning abilities, linguistic competence, common sense, or social skills of a five year old.

So, like bots, robots will no doubt become increasingly useful. But, as a result of tunnel design, they will probably also become increasingly frustrating to use. In that regard they may indeed seem anti-social. But they are unlikely to be anti-social in the way of science fiction fantasies, with robot armies exterminating human society. Indeed, the thing that handicaps robots most of all is their lack of a social existence. For it is our social existence as humans that shapes how we speak, learn, think, and develop common sense. All forms of artificial life (whether bugs or bots) will remain primarily a metaphor for — rather than a threat to — society at least until they manage to enter a debate, form a choir, take a class, survive a committee meeting, join a union, build a lab, pass a law, engineer a cartel, reach an agreement, or summon a constitutional convention. It is these critical social mechanisms that allow society to shape its future. It is through planned, collective action that society forestalls expected consequences (such as Y2K) and responds to unexpected events (such as epidemics).

One Small Step for Futurology, One Large Step for Mankind

Why does the threat of a cunning, replicating robot society look so close from one perspective, yet from another quite distant? The difference lies in the well-known tendency of futurologists to count "1,2,3 ... a million" or even infinity. Once the first step on a path is taken, it's very easy to assume that all subsequent steps are trivial. So, for example, the telephone had barely appeared before people were predicting videophones — yet we still don't have videophones on any large scale today. Several of the steps Joy asks us to take — from genetic engineering to a White Plague, from simulations to out-of-control nanotechnology, from replicating peptides to a "robot species" — are extremely large. And they are certainly not steps that will be taken on an open highway without potholes, diversions, regulations, controls, or traffic coming the other way.

One of the lessons of Joy's article, then, is that the path to the future can look simple (and sometimes simply terrifying) if you look at it through what we call 6-D lenses. We coined this phrase having so often come upon "de-" or "di-" words like *demassification*, *decentralization*, *disintermediation*, *despacialization*, *disaggregation*, and *demarketizatio*n in futurology. These are grand forces which some futurists see technology blowing through society and uprooting our social systems like an irresistible storm. If you take any one of the Ds in isolation, it's easy to follow its relentless journey to a logical conclusion. So, for example, because firms are getting smaller, it's easy to assume that firms and other intermediaries are simply disintegrating into markets. And because communication is growing cheaper and more powerful, it's easy to believe in the "death of distance." But these Ds rarely work in such linear fashion. Other forces (indeed, even other Ds) are, we need to remember, at work. Some, for example, are driving firms into larger and larger mergers to take advantage of the social (rather than just technological) networks. Other forces are keeping us together despite the availability of great communications technology. So, for example, whether communications technology has killed distance or not, people curiously just can't stay away from the social hotbed of modern communications technology, Silicon Valley.

Importantly, the Ds do indicate that the old ties that bound communities, organizations, and institutions are being picked apart by technologies. A simple, linear reading then suggests that these will now simply fall apart. A more complex reading, taking into account the multiple forces at work, offers a different picture. Undoubtedly some communities, organizations, and institutions will disappear. But others will reconfigure themselves. So, while many nationally powerful corporations have shriveled to insignificance, some have transformed themselves into far more powerful transnational firms. And while some forms of community may be dying, others bolstered by technology are growing stronger.

Two hundred years ago, Thomas Malthus, assuming that human society and agricultural technology developed on separate paths, gloomily predicted that society was growing so fast, it would starve itself to death. A hundred years later, H.G. Wells similarly assumed that society and technology were developing independently. Wells, however, like many today, saw technology outstripping society. So he predicted that technology's relentless juggernaut would unfeelingly crush great swathes of society. Like Joy, both Malthus and Wells issued important warnings, alerting society to dangers it faced. But by their actions, Malthus and Wells helped prevent the very future they were so certain would come about. These self-*un*fulfilling prophecies failed see that, once warned, society could wittingly and unwittingly galvanize itself into action. It could develop agricultural technology to increase the food supply dramatically. And it could develop social constraints to temper the exuberance of technology. Of course, this social action in the face of threats showed that Malthus and Wells were most at fault in their initial assumption. Social and technological systems do not develop independently. The two evolve together in complex feedback loops, wherein each drives, restrains, and accelerates change in the other.

Of course, once the social system is factored back into prognostication, the road ahead looks much more convoluted. It is difficult to know what might lie beyond the next bend and which way it is best to turn. But this much can certainly be said. Communities, organizations, and institutions are indeed the main brake by which society slows the destructive power of technology (and, indeed, accelerates its advantages). As new technologies emerge, old institutional forms (copyright and patent law, government agencies, business practices, social mores, and so forth) inevitably prove inadequate. Consequently, society has to develop new ones. Robert Putnam's new book, *Bowling Alon*e, shows this process in action. The dawn of the 1900s brought unprecedented technological advances, including the introduction of cars, airplanes, telephones, radio, and domestic power. With these advances came first, unprecedented social disruption, and then a remarkable period of legal, government, business, and societal innovation — stretching from the introduction of anti-trust legislation to the creation of the American Bar Association, the Sierra Club, the American Red Cross, the NAACP, and the YWCA. Society, implicitly and explicitly, took stock of itself and its technologies and acted accordingly. The resulting social innovation has left marks quite as deep as those left by technological innovation.

To deal with recent unprecedented technological change and the disruption it may cause, we will need similarly extensive and unprecedented social reflection and similar organizational and institutional creativity. New social forces, however, take time to develop. And the more people ignore them, the more time development will need. But technological acceleration gives us ever less time. So first the public at large needs to become engaged in these debates and to understand that society and institutions are part of the whole picture — something technological tunnel vision obscures. That way we can all see where the brake lies. Then we need to consider how an educated public can help construct new social institutions. That way, we can start to apply the brake where necessary.

NATIONAL NEEDS DRIVERS FOR NANOTECHNOLOGY

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Abstract

Nanoscience and nanotechnology may turn out to have significant societal implications, as would be the case for any truly revolutionary advance in technology. We have identified three areas — natural resources, human condition, and security — where trends are raising significant social issues that will become drivers for technological change. To achieve a safe, secure world we must consider both global and national aspects of security, and the above issue areas are significant in this broader context. These problems are complex and require a life cycle systems approach for technological advances to contribute to real societal solutions. Finally, as with any radically new technology, the consequences of using nanotechnologies can harm as well as help mankind. It is up to society to debate and develop total and durable solutions.

Introduction

The Clinton Administration's National Nanotechnology Initiative was instituted to

> …support long-term nanoscale research and development leading to potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, environment, energy, chemicals, biotechnology, agriculture, information technology, and national security. The effect of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century. (NSTC 2000)

We argue that a government research and development initiative of this scale should go one step farther: the breakthroughs sought should relate to the central emerging problems of our society. While curiosity and unforeseen discoveries will still motivate the science, the scientific effort should point in the general direction of contributing elements to systems solutions to the complex challenges that face our nation. We need to think at an early stage about how nanotechnology will affect "the health, wealth, and lives of people."

Coming from a national security laboratory, we tend to think of most of the potential nanotechnology applications as having national security implications. Figure 6.5 suggests that national security cannot be independent of global security. But global security encompasses many more dimensions than just the military. The consequences of economic and informational globalization, combined with emerging demographic changes, will bring new kinds of threats to national and international security. Individual

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[*] Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000

national security in a world of global collapse will not be tenable. We will have to seek national security in a context of global security (upper left quadrant of Figure 6.5).

At our nuclear weapons laboratory, we tend to think of problems in terms of systems and life cycles. (Sandia has responsibility for the non-nuclear systems in nuclear weapons from concept to production, to maintenance, and finally to dismantlement.) An example of a technology area where we as a nation did not work the entire life cycle problem is that of nuclear power. By not solving the nuclear waste disposal problem adequately as we developed the power generating systems, we left ourselves with a sizeable unresolved societal problem.

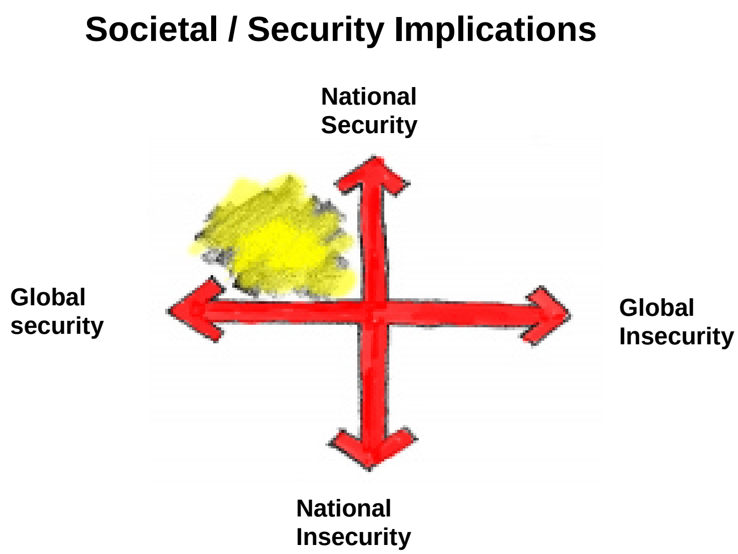

Figure 6.5. A Secure nation in a secure world.

Our analysis of the conditions for global and national security leads us to consider three broad issues. The first revolves around the condition of the planet and its natural resources. We'll refer to this as the "green" issue involving foremost water, energy, and the environment. The second broad issue, which we call "red," is that of the human condition, with health at its center. These first two areas are potential sources of conflict that can drive global insecurity if unresolved. If it fulfills its promise, nanotechnology can enable solutions to many problems within these "red" and "green" issues areas. The third issue — which we call "black" — is military, for example as in the area of bio-warfare. Military advances enabled by nanotechnology, if used wisely in the interests of global security, can help to maintain a just peace. If used for purposes of aggression and domination, they can pose a substantial risk to all.

Natural Resources

There appears to be an increased potential for conflict as a rapidly growing world population tries to sustain itself with limited natural resources (Nichiporuk 2000; Brown, Flavin, and French 2000). The disparity in wealth between developed and developing nations, in combination with the uneven distribution of natural resources, remains a threat to the stability of states and of the international system. With the advent of modern manufacturing, advanced technologies, and the information age, the importance of natural resources has been reduced for developed nations. But, especially for developing nations, the availability and control of critical resources such as oil, water, and food on an increasingly crowded planet remain among the major sources of long-term insecurity. It is possible that nanotechnology will contribute to easing resource disparities. Potential areas of impact include new materials, potable water, new energy sources, and sustainable environmental processes.

The availability of water resources remains one of the big issues for potential insecurity around the globe. As the World Commission on Water for the 21st Century has pointed out,

> What is obvious is that progress, especially in developing countries, is much too slow, and that unless there are drastic changes, water shortages and environmental degradation will become the norm. More people than ever will be added to some of the areas of the planet that are already most vulnerable socially, economically, and environmentally. (World Water Council 2000)

Low cost techniques for water purification, self-cleaning, evaporation reduction, and desalination could have tremendous impact by providing adequate supplies of clean water. A major driver for regional conflict might be removed. Adequate water supplies are necessary not only for human health, but also to assure the availability of food for the developing world's growing population. The potential impact of nanotechnology on water supplies is hard to predict at this time, but several areas of significant opportunity come to mind. Affordable, engineered membranes that incorporated a self-cleaning process to avoid fouling could be used for large-scale desalination, which would go far in solving the water resource problem. While this technology would be a significant leap from current capabilities, the ability to tailor nanoscale membranes in combination with advances in self-assembly processes make it one to watch. In a variation on this concept, the ability to create membranes with molecular receptors that preferentially extract heavy metals and other pollutants is making progress in Department of Energy and other research laboratories (Roco et al. 1999). Another potential means of preserving water resources, particularly for agriculture, may be the control of evaporation through large-scale application of nano-engineered films or membranes. Management of water resources is a good example of where the life cycle systems approach should be taken to assure that the technologies employed do not leave unanticipated environmental problems in their wake.

A second "green" issue of growing long-term concern for global security is that of energy resources and their use. Although proven reserves of oil and natural gas are large, heavy energy usage by the developed countries, combined with the demographic and development trends of the third world, will eventually put pressure on the supplies. (With less than 5% of the world's population, the United States accounts for about 25% of world energy consumption.) In the meantime, the burning of fossil fuels has at least the possibility of substantially degrading the global environment.

Nanotechnology may be able to ameliorate energy problems both on the supply side and on the use side. In the near term, new, high-strength nanostructured magnets, nanolubricants, and other improved materials may greatly improve motor efficiency. In the long term, nanoengineered fuel cells, biocatalysts for crops for food or biomass fuels, or nanostructured photovoltaic films may permit cheaper alternative energy sources. For example, if the efficiency of photovoltaics were improved by a factor of two from the 20 to the 40% range at comparable costs — something that is theoretically possible — the role of solar energy would grow substantially. Likewise, if the oceans could be used for growing biomass fuels or harvesting energy through nano-biotechnology advances, significant increases in global energy supplies would result.

Systems life cycle thinking is particularly important in addressing the energy issue because of the coupling of energy and the environment. For example, if artificially engineered plants that produce ready-to-use energy become possible, at an early stage we will have to address issues akin to those now arising from the field of genetically engineered foods. But, properly designed, systems using such technologies as photovoltaics, engineered photosynthesis, factory process heat re-use, or agricultural fuel production could lead to a world of sustainable energy, agriculture, and climate. Such an "open system biosphere" (see Figure 6.6) would clearly have enormous implications for global security.

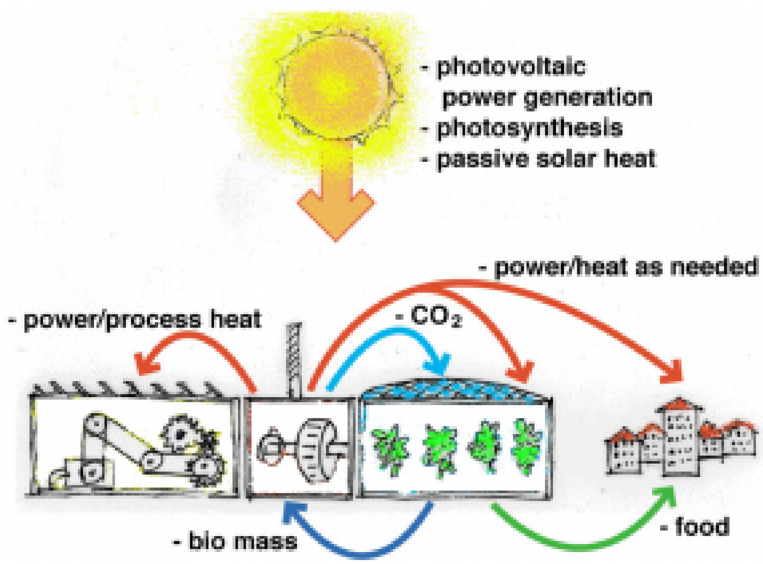

Figure 6.6. Open System Biosphere — a city model for sustainable energy, agriculture, and climate.

Nanoscience may also enable new materials and technologies that reduce economic dependence on other kinds of natural resources. The dependence of nations on extraction resources might be altered if common materials could achieve the functions of rarer and more costly materials. We refer to the ability to nanostructure a material for specific desired properties not found in its usual forms as *nano-alchemy*. In essence one is creating a new material by nanostructuring rather than by merely changing the chemistry. For example, common materials in the form of nanoscale clusters have been demonstrated to take on specific chemical catalytic properties, superior to those of more expensive catalysts. At this point we cannot predict whether nano-alchemy will apply broadly, or at what cost, but it is possible to envision large changes in how industries work. Then the relative wealth and power of nations could change, as could some of the contributing sources of international conflict.

Note, however, that there are no guarantees that the unregulated marketplace will assure a distribution of the benefits of nanotechnology that brings widespread prosperity and tranquillity. It is also possible to imagine the new technologies being used in ways that help the rich get richer and the poor get poorer. Given that nanoscience is being funded on a large scale from public resources, it behooves us to think on a national level about how its fruits can be directed to enhance national and international prosperity and security

Human Condition

The human condition — the "red" issue — also must be considered in an analysis of the potential societal implications of nanotechnology. In the United States the proportion of the population at retirement age is increasing and will continue to grow rapidly over the next several decades, with a corresponding decrease in the available fraction of workers in the society. This trend has been strong in the developed countries where the birth rate has declined significantly, leading to low or even negative population growth, while life expectancy has been increasing. With an aging population, an increasingly large fraction of national and personal resources is being spent on health care. Here, we will not discuss the additional, very serious health issues, such as AIDS and other emerging infectious diseases that burden developing countries. We would note, however, that if the applications discussed above of nanotechnology to securing clean water were to prove out, they could help with the disease problems of developing countries by improving sanitary conditions.

Desirable goals for an aging population include maintaining productivity longer, providing affordable health care, and deploying assistive technologies that maintain independence longer. Achieving these goals would greatly reduce the burden that an unhealthy, dependent older generation would place on younger citizens. The economic and social benefits to the nation would be great. We consider here just two possible connections to nanoscience and nanotechnology: assistive means to maintain physical independence and tools to support cognitive capability.

In the area of assistive devices, the ability to see (eye repair or hardware to replicate the eye function) and to maintain mobility (prostheses and sensor-based systems) could contribute significantly to maintaining productivity and physical independence. Advances in micro and nanotechnologies hold promise for contributing to a wide range of assistive solutions, from prosthetic limbs that adjust to the changes in the body, to more biocompatible implants, to artificial retinas or ears. Other opportunities lie in the area of neural prosthesis and the "spinal patch," a device envisioned to repair damage from spinal injuries.

In the area of cognition, revolutionary technical advances could have great impact on individual productivity and independence. We do not understand the workings of the brain well enough to predict with any confidence that assistive devices will actually work. However, rapid advances in the intersecting nano-, information science, and biological sciences seem to promise significant surprises. Possible results include devices that enhance learning, cognition, judgement and decision making. Devices that helped people with dementia — nearly a third of the population over 85 — could have great impact. At the same time concerns about the use of artificial or assisted cognition for social control must be addressed.

As with the potential benefits of technologies relating to natural resource use, those relating to human health and quality of life also could end up being available only to small segments of the world's population. Today we talk of the "digital divide"; tomorrow it may be the "nano divide." Only the right combinations of public policy (from whence a significant part of the initial investment in nanoscience is coming) and free enterprise will lead to maximizing the societal benefits of the new technologies.

Security

There is little doubt that nanoscience and nanotechnology will carry implications for the use of force for military and civilian security. Military and police organizations would highly value enhanced situational awareness in a world of ambiguity, confusion, and asymmetric threats. The implications of advances in computing speed, higher density memories, enhanced sensing and communication, and microsystems that, individually or in swarms, may contribute to situational awareness and control are obvious. Nanoscience will enhance all of these technologies. Implications of such advances range from distributed early warning, assessment, and response systems, to enhanced decision support systems. New non-lethal weapons may also emerge.

One area in which our understanding is rapidly growing is that of the emergent behavior of collective systems (see Figure 6.7). For example, researchers are beginning to appreciate how bees, with limited individual capabilities and simple rules of interaction, are collectively able to complete complex tasks, such as finding and harvesting nectar. Nanoscience, understanding of cognition, and microtechnologies may combine to give us small, smart devices that sense, think, act, and communicate as swarms. Robotic swarms might play important roles in both security situations and natural disasters where direct human presence would be dangerous or ineffective.

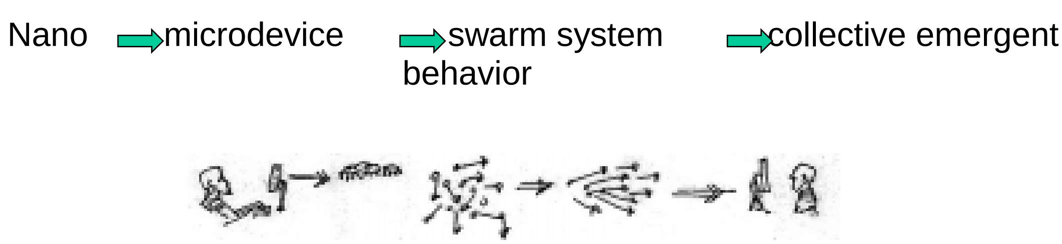

Figure 6.7. Nanotechnology may be a key enabling element to creating small, smart swarms of devices that sense, think, act, and communicate — resulting in emergent behavior of collective systems.

New information technology (possibly nanotech enabled) combined with better understanding of human and machine cognition, may give us new decision support systems. Information display and data fusion are already important military technologies. If memory aids (information storage and analysis) can be integrated with the human brain for decision support, applications in areas beyond military and emergency situations may become available. Related technologies would be interface devices such as wireless communication to the ear or displays on the retina, or reasoning support systems that would serve as decision advisors.

These various advances could contribute to global stability by enhancing the capabilities of peacekeepers to operate in difficult circumstances or of soldiers to resist aggression. As with other enhancements of military capability, however, they could also contribute to the success of military aggression. If the technologies were cheap and widely available, they could expand threats from terrorist or paramilitary groups.

Disruptive Technologies[1]

"Disruptive technologies" are those which produce new products in new ways. Initially, they may cost more and be less effective than the more mature, "sustaining technologies." But eventually, they become so much cheaper and better as to drive the older technologies out of the market. The technologies emerging from nanoscience may well prove disruptive. If so, they will have societal implications that extend beyond their functional applications and into the realms of industry and economy (see Figure 6.8). Particular manufacturing firms, and perhaps entire industries (e.g. petroleum, agriculture), might be deeply changed, or even shrink to insignificance. Some managers and workers might be put out of business, while others may prosper. Those with the resources and adaptability to retrain may succeed, while others — perhaps especially older workers — may not make the transition successfully. Redistributions of economic power could lead to corresponding redistributions of political influence.

The international status of the nations which first master the new technologies may rise, while the nations overly committed to old industrial processes or to extracted resources may fall behind. As on the national level, redistributions of global technological strength could result in realignments of global prosperity and influence. These changes could promote national and international stability and security — or they could hinder it.

Conclusions

Nanoscience and nanotechnology may turn out to have significant societal implications, as would be the case for any truly revolutionary advance in technology (Figure 6.8). We have identified three areas — natural resources, human condition, and security — where trends are raising significant social issues that will become drivers for technological change. To achieve a safe, secure world we must consider both global and national aspects of security, and the above issue areas are significant in this broader context. These problems are complex and require a life cycle systems approach for technological advances to contribute to real societal solutions. Finally, as with any disruptive technology the advances brought about can be used for good or evil. It is up to society to debate and develop total and durable solutions.

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[1] A term coined by Clayton M. Christensen (Christensen 2000).

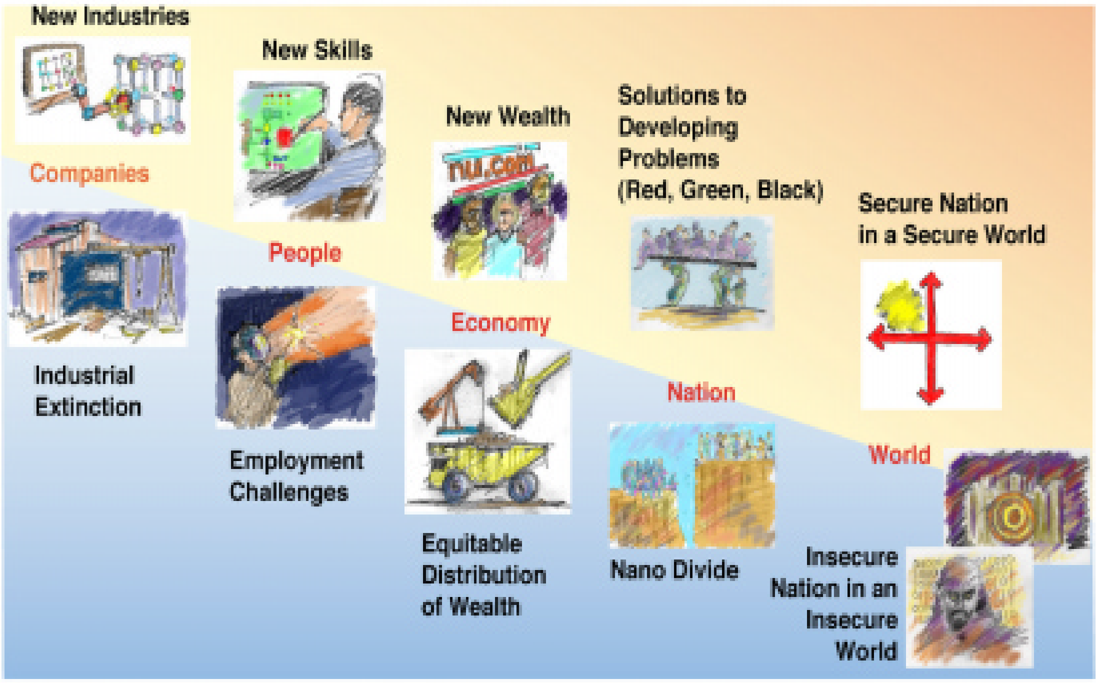

Figure 6.8. Nanotechnology may fall into the category of disruptive technologies where significant new capabilities and industrial systems bring large-scale changes, which may result in the betterment of society or may create new problems.

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NANOTECHNOLOGY AND SOCIETAL TRANSFORMATION

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Remaking the World

Technological innovation sustains a fundamental tension of civilization — the tension between humanity's quest for more control over nature and the future, and our equally strong desire for stability and predictability in the present. Luddites were not against technology per se. They were against losing their jobs, and so they smashed the power looms that had put them out of work. The change wrought by technological advance continually remakes society, and this transformational process is on the one hand central to the dynamic that is commonly labeled "progress," and yet on the other is a source of continual destabilization and dislocation as experienced by individuals, communities, institutions, nations, and cultures.

In the age of science and technology (S&T), the federal government has increasingly become the prime catalyst for scientific advance and technological innovation. At the same time, modern government is also continually responding to and managing the transformational power of science and technology. Yet there is little effort to understand the relation between these two critical activities — advancing knowledge and innovation, and responding to their impacts — or to link them in a way that can enhance the value and capability of each.

A single technological innovation can remake the world. When the metal stirrup finally migrated from Asia to Western Europe in the 8th century, society was transformed to its very roots. For the first time, the energy of a galloping horse could be directly transmitted to the weapon held by the man in the saddle — a combat innovation of devastating impact. Because horses and tack were costly, they were possessed almost exclusively by landowners. Battlefield prowess and wealth were thus combined, and from this combination grew not just the traditions of a "warrior aristocracy" but the structure of European feudal society itself. Later, when the Anglo Saxon King Harold prepared to defend Britain against the invading Normans in 1066, he actually dispensed with his horse and ornamental wooden stirrups, choosing to lead his numerically superior forces on foot. The outnumbered Normans, however, boasted a strong, stirrup-equipped cavalry, and thus won the day — and the millennium (White 1962).

Such narrative has the ring of mythology, yet the experience of the industrialized world reinforces the knowledge that a new machine can help change everything. The invention of the cotton gin in the late 18th century allowed a vast expansion of cotton cultivation in the American south — and directly fueled a commensurate rise in the importation and use of slaves for plantation labor. One hundred and fifty years later, the mechanical cotton picker suddenly rendered obsolete the jobs of millions of African American share croppers, and catalyzed a 30-year migration of five million people out of the rural south and into the cities of the north. While the development of the mechanical cotton picker was no doubt inevitable, its proliferation was consciously accelerated by plantation owners who, fearing the rise of the civil rights movement, sought quickly to find a technological replacement for the existing system of exploitation labor upon which they were economically dependent (Lemann 1991).

These examples point not only to the power of new technologies to transform society, but to the comprehensive interconnectedness of technological change and the complex social structure of society. The invention of the stirrup as a battlefield tool was in some very intricate way connected to the development and expansion of feudalism in Europe; the evolution of agricultural technology for a single cash crop is indissolubly bound to the ongoing struggle to overcome the U.S. legacy of slavery, segregation, and bigotry. More familiarly, a single class of technology — nuclear weapons — was a central determinant of geopolitical evolution after the end of World War II. Cars, television, air conditioning, and vaccinations have all stimulated foundational changes in society during the past century.

Of course new technologies rarely emerge in isolation. The industrial revolution is not just the story of harnessing steam power to factory production capability, but also the story of technological revolutions in transport, communication, construction, agriculture, resource extraction, and, of course, weapons development. These technological systems penetrated the innermost niches of society — home and family, school, workplace, community — and forced them to change. They also introduced completely new social phenomena, and stimulated the invention of completely new institutions.

The industrial revolution created the macroeconomic phenomenon of unemployment. Prior to the 19th century, even the most economically and politically advanced societies were dominantly agrarian and rural. For the majority of people, work was rooted in the home and the family. Vagaries of weather and transportation imposed irregularities and hardship, but most people and families harbored a diversity of skills that gave them independence from the marketplace and resilience to cope with a variety of challenges. In hard times, resort to subsistence farming and barter was usually possible (Keyssar 1986).

Industrialization and urbanization linked workers far more closely to the larger economic market, while removing the need and ability for them to maintain the diverse skills necessary for survival in the pre-industrial world. The traditional connection between manufacturing and agriculture in the home was sundered by new economic organization and by geography. Labor itself became a commodity, subject to the same fluctuations and influences as other commodities. During an economic downturn, factories fired people or closed down entirely. For the first time, workers could not easily respond to changing economic conditions by switching to a different type of work or moving to a subsistence mode. The political economist Karl Polanyi observed: “To separate labor from other activities of life and to subject it to the laws of the market was to annihilate all organic forms of existence and to replace them by a different type of organization, an atomistic and individualistic one” (Polanyi 1944, 163).

As technological innovation interacts with society to create new phenomena, such as unemployment, society also responds by developing new types of institutions and response mechanisms. Today we can recognize the problem of unemployment as central to a diversity of social, political, and economic structures and activities ranging from the organization of labor to insurance safety nets to educational programs to immigration policy. Unemployment rates are a key indicator of economic health, and a key determinant of political behavior. National and international economic policies focus strongly on managing unemployment, even as theoretical investigations seek to clarify the relation between unemployment rates and other key attributes of modern economies.

The general point is that transformational technology represents one variable in a complex assemblage of dynamic, interrelated societal activities. Decision making processes tend to address each of these activities in isolation from the others, e.g., conduct of research and development (R&D), dissemination of innovation products, development of regulations, reform of institutions. Concerted action occurs when a given innovation stimulates enough transformation to demand a response from other sectors of society. This response then triggers additional changes, which in turn demand further modulation. The process is reactive, discontinuous, disruptive, and sequential — like billiards. The challenge is to move toward a process of technology-supported societal progress where different sectors and activities can continually coevolve in response to knowledge about one another's needs and constraints — like an ecosystem. We are not there yet.

Transforming the Present

A brief consideration of evolution of information technologies helps to bring this look at societal transformation into the present. Gutenberg's perfection of the printing press of course had enormous transformational impact, allowing the broad dissemination of written texts and consequent expansion of information — and literacy — that undermined the Church's hegemony over knowledge and culture, and helped promote the dissolution of medieval social structure. Lewis Mumford suggested that the printed word represents "the media of reflective thought and deliberate action," a prerequisite, perhaps, for the intellectual achievements of the Enlightenment. But he also observed — as early as 1934 — that new modes of electronic communication were increasing the speed of information exchange to levels that made reflection impossible, and increasing the volume of information transmission to a point that exceeded our absorptive capacity (Mumford 1934, 240).

The implications of the information and communication revolution on democracy itself are far from clear. On the one hand, proliferation of information dissemination networks means greater access by more people to more information — and a greater capacity to communicate one's ideas and preferences in democratic fora. Control of information by authoritarian governments is becoming increasingly futile, and organization of democratic opposition increasingly enhanced, by new information technologies. But when this same capacity translates into 10,000 identical e-mail messages sent to a Member of Congress in support of a particular bill, one is hard-pressed to suggest that democracy is the beneficiary. Of particular concern is the recent increase in public referenda aimed at bypassing the legislative process. The barriers to putting referenda on ballots have been enormously reduced by information and communication technologies that can be used to disseminate ideas and organize group action with relatively little effort. While on the one hand this type of direct democracy can be a refreshing antidote to sclerotic legislative process, on the other it is quite often devoid of any serious deliberative process or public discourse, reflecting perhaps the pique of one well-organized interest group or individual, and the substantiation of a Warholian politics where anyone with access to a decent list-serve can lead a movement for a day. Is democracy in transition?

The implications of the information and communications revolution on the distribution of economic benefits in society are also problematic. Does the troubling increase in wealth concentration that characterizes both the U.S. and the global economy derive from the way that advanced technologies diffuse in market economies? Does the synergistic character of information and communication networks mean that disenfranchised populations and nations will find it increasingly difficult to participate in the spectacular economic growth that we have seen in the past decade? In other words, are the benefits of technology becoming increasingly appropriable by particular sectors of society, and is this in part an attribute embodied in new types of technological systems? Society is ill-prepared to answer such questions, let alone act on them in a knowledgeable manner.

Paradoxically, concerns about appropriability cut both ways. In the information society, the increasing ease of information dissemination may also threaten our system for protecting intellectual property and innovation. From pirated CD's sold on the streets of Shanghai to the advent (and apparent demise) of NAPSTER, the concept of intellectual property seems increasingly vulnerable. Are we looking to a future where such protection is no longer practically possible? Does a world without patents and copyrights seem unimaginable? More unimaginable than, say, the loss of monopoly over the written word would have seemed to the Church in 1450?

At issue here is not the value of change, but the path that change follows. What may look in retrospect like the march of progress may be experienced in real time as wrenching dislocation. The Dickensian squalor of 19th century London remains a symbol of the human impacts of technological change. Faced with unprecedented societal transformations, the English government (as well as other European states) failed to develop effective policies that could accommodate the rapid transition from rural agrarian to urban industrial society. Today, the plight of many overpopulated developing nations is the post-industrial, global manifestation of the same failure.

We see the fingerprints of societally transforming technological systems in the controversy over genetically modified organisms; in the morally reprehensible situation where 24 million HIV-positive sub-Saharan Africans cannot possibly afford AIDS drugs that are widely available in the affluent world; in the existence of 40 million Americans with no medical insurance; in the general inability of our public school systems to create a citizenry able to take advantage of the opportunities of the knowledge economy; in the challenges presented by the aging of our population; in the rising atmospheric carbon dioxide levels that symbolize 150 years of industrial dynamism.

Even the unprecedented rise of civil and ethnic conflict throughout the world in the past decade can be plausibly connected to technological transformation. Approaching this phenomenon from entirely different directions, the political scientists Samuel Huntington and Benjamin Barber each conclude that advanced communication and information technologies have created new fora for expressing ethnic identity and pursuing and strengthening cultural solidarity. Virtual communities, for example, can act to maintain identity over great distance, while also more efficiently garnering resources to support the expression of cultural goals. As Barber observes: "Christian Fundamentalists [can] access Religion Forum on CompuServe Information Service while Muslims can surf the Internet until they find Mas'ood Cajee's Cybermuslim document." The result may be locally empowering and globally divisive (Barber 1996, 155-156; Huntington 1996).

Nanotechnology and Societal Transformation

The marriage of science and technology beginning in the latter part of the 19th century accelerated the process of innovation, and thus the process of societal transformation as well. If the industrial revolution played itself out in less than 200 years, the electronics revolution seems likely to have a working life of perhaps 75 years, while the biotechnology revolution, although hardly yet on its feet, is already prophesied to be supplanted by (or perhaps to morph into) the nanotechnology revolution in the first half of the new century. What type of transformations might this revolution have in store?

Our point here is not to predict the future of nanotechnology and its impacts — an impossible goal — but to illustrate the direction and scale of thinking that will be necessary if we are to successfully manage the interaction of new knowledge and innovation with society. Judging by the literature prepared by the government (NSTC 1999; NSTC 2000), as well as the work of futurists and other techno-pundits (e.g., Cetron and Davies 1997), the promise of nanotechnology to remake our world seems virtually infinite. So the first thing to say is that if — as is variously claimed — nanotechnology is going to revolutionize manufacturing, health care, travel, energy supply, food supply, and warfare, then it is going, as well, to transform labor and the workplace, the medical system, the transportation and power infrastructure, the agricultural enterprise, and the military. Each one of these technology-dependent sectors is operated by and for human beings, who act within institutions and cultures, according to particular regulations, norms, and heuristics, all of which may reflect decades or even centuries of evolution and tradition. Not one of them will be "revolutionized" without significant difficulty. The current chaos in our medical system is emblematic of this type of difficulty.

In the near term, the current state of knowledge may suggest that the first wave of useful nanotechnologies will lie in the area of detection and sensing. The capacity to detect, precisely identify, and perhaps isolate single molecules, viruses, or other complex, nanoscale structures has broad application in such areas as medical diagnosis, forensics, national defense, and environmental monitoring and control. The potential for direct benefits is obvious; how might this evolving capacity influence society?

When detection outpaces response capability — as it usually does — ethical and policy dilemmas inevitably arise. For example, it is already possible to identify genetic predisposition to certain diseases for which there are no known cures, or to diagnose congenital defects in fetuses for which the only cure is abortion. In the environmental realm, new technologies that detect pollutants at extremely low concentrations raise complex questions about risk thresholds and appropriate remediation standards. The presence of tiny amounts of toxic materials in groundwater may justifiably raise alarm among the public even if the health risk cannot be assessed, and the technological capacity for remediation does not exist. These types of dilemmas may be expected to accelerate and proliferate with the advance of nanodetection technologies.

Advances in sensing and detection may transform existing societal mechanisms and institutions that were designed to cope with uncertainty and incomplete or imprecise information. The insurance industry, for example, deals with incomplete knowledge about the health of specific individuals by spreading its risk among large populations. If there is no way to distinguish between someone who is going to suffer a potentially lethal middle-age heart attack, and someone who is going to live to 105, then they can both get health and life insurance. Society clearly gains from this arrangement: costs are broadly disseminated, and benefits are delivered to those who most need them.

Medical sensors that can, for example, “detect an array of medically relevant signals at high sensitivity and selectivity” (NSTC 2000, 45) promise to aid diagnosis and treatment of disease, but also to develop predictive health profiles of individuals. Today, health and life insurance companies often use pre-existing conditions as a basis for denying or restricting coverage. The advent of nanodetection capabilities will considerably expand the information that insurance companies will want to use in making decisions about coverage. The generation of new information might thus destabilize the risk-spreading approach that allows equitable delivery of social benefits to broad populations. How will society respond?

Nanotechnology offers a dizzying range of potential benefits for military application. Recent history suggests that some of the earliest applications of nanotechnology will come in the military realm, where specific needs are well articulated, and a customer — the Department of Defense — already exists. One area of desired nano-innovation lies in the “increased use of enhanced automation and robotics to offset reductions in military manpower, reduce risks to troops, and improve vehicle performance.” (NSTC 2000, 20). How might progress in this realm interact with the current trend toward rising civilian casualties (in absolute terms and relative to military personnel) in armed conflict worldwide? As increased robotic capability is realized in warfare, will we enter an era when it is safer to be a soldier in wartime than a civilian?

Such considerations are simple extrapolations of current trends in technological innovation and societal transformation. More adventurous speculation is tempting but is perhaps best confined to science fiction novels. The question of public response to nano-innovation, however, should not be avoided, even at this early stage. The ongoing experience of public opposition to old technologies such as nuclear power, new technologies such as genetically modified foods, and prospective technologies such as stem cell therapies, needs to be viewed as integral to the relationship between innovation and societal transformation.

Three observations are particularly relevant here. First, the impact of rapid technological innovation on people’s lives is usually not consensual. Second, in the short term at least, the social changes induced by new technologies usually create both winners and losers (where what is lost may range from a job to an entire community). Third, rapid technological change can threaten the social structure, economic stability, and spiritual meaning that people strive in their lives to achieve. As the nanotechnology revolution begins to unfold in all its promise and diversity, such issues are bound to express themselves. They should not be viewed as threats, or as manifestations of intellectual weakness or repugnant ideology. Rather, they need to be recognized as a central part of the human context for technological change.

Preparing for the Revolution

> Now nanotechnology had made nearly anything possible, and so the cultural role in deciding what should be done with it had become far more important than imagining what could be done with it. (Stephenson 1995)

When resources are allocated for R&D programs, the implications for complex societal transformation are not considered. The fundamental assumption underlying the allocation process is that all societal outcomes will be positive, and that technological cause will lead directly to a desired societal effect. The literature promoting the National Nanotechnology Initiative expresses this view. The current policy approach thus addresses two elements:

- Conduct of Science and Technology
- Products of Science and Technology

These elements reflect the internal workings of the R&D enterprise. The fact that societal outcomes are not a serious part of the framework seems to derive from two beliefs: (1) that the science and technology enterprise has to be granted autonomy to chose its own direction of advance and innovation; and (2) that because we cannot predict the future of science or technological innovation, we cannot prepare for it in advance. These are oft-articulated arguments, not straw men. Yet the first is contradicted by reality, and the second is irrelevant. The direction of science and technology is in fact dictated by an enormous number of constraints (only one of which is the nature of nature itself). And preparation for the future obviously does not require accurate prediction; rather, it requires a foundation of knowledge upon which to base action, a capacity to learn from experience, close attention to what is going on in the present, and healthy and resilient institutions that can effectively respond or adapt to change in a timely manner.

If we flip the current S&T policy approach on its head, and start by thinking about desired social outcomes, rather than desired inputs to the R&D enterprise (i.e., more money), where would we begin? We might identify several very general categories of outcomes that most people would agree are worth thinking about. For example:

- Social equity: the distribution of the benefits of science and technology.
- Social purpose: the actual goals of societal development that we want to pursue or advance.
- Economic and Social enterprises: the shape and make-up of the institutions at the interface between technology and the human experience.

How can consideration of these types of outcomes be integrated into the S&T policy framework? The years since World War II have seen a very gradual evolution in the effort to connect thinking about S&T to thinking about the outcomes of S&T in society. A science policy report issued by the Truman Administration, for example, mentioned in its first pages the need to prepare for both the positive and negative impacts of scientific and technological change (Steelman 1947, viii). The rise of the environmental movement in the late 1960s reflected a public demand that society devote more S&T resources to the achievement of desired social outcomes like clean air and water. The creation of the congressional Office of Technology Assessment reflected growing public concern about the need to understand the societal implications of technological choices. Over the past decade, federally funded programs on the human dimensions of global climate change, and the ethical, legal, and social implications of the human genome project and information technologies, have been supported as adjuncts to much, much larger core research agendas in the “hard” sciences. Yet S&T policy itself remains input-driven.

Concepts such as sustainability, and analytical tools such as human development indicators, provide conceptual frameworks for linking R&D to societal outcomes, and in fact imply that outcomes are to some degree implicit in the choices we make about R&D inputs. These types of insights point the way toward the next step: to implement an approach to R&D policy that addresses the complex interconnections between technological advance and societal response. Such an approach would need to integrate the pursuit of innovation with an evolving understanding of how innovation and society interact, and include mechanisms to feed this understanding back into the innovation process itself. (In a very specific way, the private sector does this as a matter of course, as it uses consumer input to continually refine and improve the next generation of products.)

If we wanted to be serious about preparing for the transformational power of a coming nanotechnology revolution, we would need first to get serious — at this very early stage — about developing knowledge and tools for more effectively connecting R&D inputs with desired societal outcomes. This in turn would require the creation of a dedicated intellectual, analytical, and institutional capability focused on understanding the dynamics of the science-society interface and feeding back into the evolving nanotechnology enterprise. Such a capability might include the following elements:

- *Analysis of past and current societal responses to transforming technologies.* A case history approach could be used to investigate the diverse avenues that society has followed in responding to a range of technological advances. Understanding the roles and relations between the media, academia, policy makers, institutions, and cultural factors could be the basis for assessing — and anticipating — the likely trajectories of technology-induced social change.

- *Comprehensive, real time assessment and monitoring of the nanoscience and nanotechnology enterprise.* At this relatively early stage, it should be feasible to build a database of important activities in nanotechnology, and then track the evolution of the enterprise over time, in terms of directions of research and innovation, resources used, public and private sector roles, publications and patents, marketed products, and other useful indicators. This type of information is essential to understanding potential impacts.

- *A science communication initiative, to foster dialogue among scientists, technologists, policy makers, the media, and the public.* Understanding, tracking, and enhancing the processes by which information about nanotechnology diffuses from the laboratory to the outside world is central to understanding the social transformation process as it occurs. Of equal importance is the need to understand and monitor how public attitudes and needs evolve, and how they reach back into the innovation system. Empirically grounded, research-based investigations on communication can be the basis for strategies to improve social choice in ways likely to secure favorable outcomes.

- *A constructive technology assessment process, with participants drawn from representatives of the R&D effort, the policy world, and the public.* Technology assessment is both a process for bringing together a range of relevant actors, and an evolving product that can inform and link the innovation and decision-making processes. Understanding the changing capabilities of both the nanotechnology enterprise and various sectors and institutions likely to be affected by the enterprise can contribute to a healthy policy making environment where innovation paths and social goals are compatible and mutually reinforcing.

Should nanoscience and nanotechnology yield even a small proportion of their anticipated advances, the impacts on society will be far-reaching and profound — "as socially transforming as the development of running water, electricity, antibiotics, and microelectronics" (NSTC 1999, 1). We can allow these transformations to surprise and overwhelm us, and perhaps even threaten the prospects for further progress. Or we can choose to be smart about preparing for, understanding, responding to, and even managing the coming changes, in order to enhance the benefits, and reduce the disruption and dislocation, that must accompany any revolution.

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