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GENERIC LESSONS LEARNED ABOUT SOCIETAL RESPONSES TO EMERGING TECHNOLOGIES PERCEIVED AS INVOLVING RISKS

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BACKGROUND

1. INTRODUCTION

Supported by the DOE Office of Science Program on Ethical, Legal, and Societal Implications of Research on Alternative Bioenergy Technologies, Synthetic Genomics, or Nanotechnologies (ELSI), a research team organized by the Oak Ridge National Laboratory is conducting a study of "Lessons Learned about Societal Responses to Emerging Technologies Perceived as Involving Risks." This project seeks (a) to consider the historical experience in the United States with developing new technologies associated with public concerns about risk, and (b) to consider how lessons learned from this experience might be relevant to societal implications of emerging technologies such as bioengineering for alternative energy production.

The central research question for the project is whether past experience in the United States with technologies associated in the public mind with risk, along with relevant social-scientific literatures, can inform strategies for emerging new technologies that are also likely to be associated with societal concerns about risks, with particular attention to possible concerns about bioenergy technologies associated with genetic engineering.

THE SCIENTIFIC AND POLICY CONTEXT

Breakthroughs in science and technology (S&T) are driving social change, seemingly at an accelerating rate. They have the potential to produce revolutionary advances in human well-being, revolutionary changes in society, and also revolutionary new hazards and risks. Meanwhile, the social organizations and institutions that produce these breakthroughs seem to be more innovative and flexible than those responsible for anticipating and coping with effects. This situation has generated serious challenges for society in the past, and the future holds promise of even more serious challenges. The practical problem for society is one of adaptive management of the consequences of S&T; the scientific problem is to develop a knowledge base that will allow adaptive management to be more than an exercise in trial and error. This project draws on (a) societal experience with the management of emerging science and technology (S&T), and (b) several broad lines of scientific theory and knowledge to contribute to that knowledge base as it is applied to potentials for bioengineering to provide significant alternative approaches for energy production.

The 20th Century brought many scientific and technological breakthroughs that had major consequences for society. These included motorized personal transport, air travel and space flight, the synthesis of new chemical compounds, the ability to harness energy from nuclear fission, and the emergence of high-speed, low-cost personal computing. Recent years have produced a steady stream of further advances, some of which will prove to be as revolutionary. In the biological sciences, these include such breakthroughs as genetic modification of organisms, xenotransplantation of organs, synthetic development of biological organisms, and genetic testing for sensitivity to toxic exposure. Each of these developments holds promise for great steps forward in human well-being, and each may radically change aspects of modern life. They may also present new kinds of hazards, ranging from inadvertent change in ecological systems to the deliberate development of biological weapons by terrorists. Generally, societal systems of control are inadequate or nonexistent for several of the possible threats (e.g., National Research Council [NRC], 2004b; Caruso, 2006).

In the physical and chemical sciences, a similarly revolutionary development is taking place. The rise of nanotechnology (Nel et al., 2006), which can create chemical entities with radically different properties from the same entities at larger scale, proceeds rapidly. These new materials promise major changes in human systems and experience, but societal systems for guiding their development are weak. Regulatory oversight that may be adequate for the release of normal materials to the environment may not be for nanomaterials. Microcomputing and micromonitoring have similar revolutionary potential, with both up- and downsides (e.g., NRC, 2002b; Mainwaring et al., 2004). They can, for example, enable low-cost sensing of human activities that can save lives, prevent crimes, and track commerce precisely, but they can also enable close surveillance of the private activities of ordinary citizens without their knowledge and at a previously unprecedented level.

Markets and governments are effective at creating and applying such breakthroughs when there is the potential for great profit or great benefits to core government priorities such as national security. But these institutions are often not so effective at anticipating and managing possible downsides, including the potential for catastrophe, for harm to the public, or for precipitous halts to development because of public concerns about the risks. And they are often insufficiently flexible to adapt to emerging concerns. Past experiences with the management of high-level radioactive waste and genetically modified foods, for instance, demonstrate that new technologies that most experts agree can be managed adequately are sometimes prevented from development through the opposition of groups in society that technology proponents believe are wrong on the science, but that have political legitimacy and some of the evidence on their side (e.g., NRC, 2001; 2002c). There is also the possibility that because of the societal allocation of decision-making authority, the full benefits of a new technology will fail to be realized. For example, emerging technologies managed entirely by private interests may yield greater societal risks and fewer societal benefits than under a regime of shared public-private decision authority.

An approach to decision making about revolutionary new developments in science and technology that shows more foresight might contribute to their effective and beneficial development. Two of the most widely recognized examples of such categories of technologies are nanotechnology and bioengineering (i.e., genetic modifications of organisms). In these two cases, both science fiction and the popular media have speculated about possible catastrophic unintended consequences, and there are similarities to nuclear energy in the sense that potentials for catastrophe seem to threaten human health and wellbeing, if not survival itself. For instance, genetic modification has stimulated concerns about possible out-of-control sequences of mutations, dangerous synthetic organisms that start epidemics, and malign applications in the hands of dangerous tyrants. The tip of the biogenetic iceberg is social concern about genetic engineering in plants and animals for human food consumption.

This project focuses first on the identification of general lessons learned from past experience with scientific breakthroughs and with risky technologies, as a basis for developing hypotheses about emergent science and technology (S&T). Examples include how public involvement relates to thresholds between acceptable and unacceptable risk and how public participation is best assured for topics involving advanced scientific content (e.g., see report of the NRC Committee on Public Participation in Environmental Assessment and Decision Making, forthcoming). It also takes advantage of the knowledge base in the social sciences and elsewhere about basic processes of societal decision making related to revolutionary advances in S&T. It will then test these general lessons by an experimental application to the case of bioengineering for alternative energy technologies, where the potential for truly new approaches to energy production are very interesting once the first goal is achieved: energy production from cellulose. Beyond that one goal lie possibilities for blue-sky alternatives that would involve more profound genetic developments and modifications to increase the ability of bio-organisms to fix energy from the sun and convert it into energy sources for human use. In these longer-term research efforts, issues of public concern about risks of genetic manipulation could become a significant issue. Hence, it would be prudent to assess that possibility.

SOURCES OF INSIGHT ABOUT SOCIETAL CONCERNS AND RESPONSES

Breakthroughs in science and technology (S&T) can present especially difficult challenges for societal control of the associated risks because of several characteristics of those risks. They may be considered to represent a subclass of problems (Rittel and Webber, 1973) that feature, in addition to difficulties of scientific and technological understanding, social complexity and potential conflict. Breakthrough S&T may simultaneously affect many dimensions of what humans value (economy, human health, ecological systems, social and economic equity, political stability), and affect different people differently. Science may be unable to anticipate with precision what the effects will be, and may even be unable to estimate the degree of the imprecision. Because people disagree about the relative importance of the values, it is impossible to aggregate the estimated effects in a non-controversial way. Moreover, decisions affecting the adaptive management of S&T often must be made before knowledge of effects becomes visible or even approximately accurate. Finally, there may be significant mistrust of decision makers and even of scientific analysts (Stern, 2005; Caruso, 2006). Thus, anticipating and coping with the effects of revolutionary S&T is a major societal challenge. Insight into the issue can be drawn (a) **inductively** from past experiences and (b) **deductively** from knowledge bases about relevant basic behavioral and social processes affecting societal decision-making.

2. INDUCTION FROM PAST EXPERIENCE

Considerable practical experience exists with societal decision making about assessing and managing the risks posed by past breakthroughs. This experience has been described and analyzed in a variety of social science studies of societal decisionmaking about particular experiences in the past and synthesized in a number of studies by individual scholars and by policy science organizations, usually focused on particular technologies or scientific developments. In many cases, National Research Council study committees and panels have been convened specifically to review scientific knowledge and the lessons of practical experience related to managing risks associated with specific breakthroughs. The following examples illustrate the nature of this knowledge base.

EXPERIENCE WITH TECHNOLOGY UTILIZATION

Over the past four decades or so, several kinds of newly emergent technologies have moved into relatively widespread use in the United States, even though issues related to societal acceptance remain unresolved in many cases. The nation's experience in these connections offers a number of lessons that may be instructive for societal decision making about other technologies, also associated with concerns, which are now emerging. Cases in point include peaceful nuclear energy use, radioactive waste management, DNA manipulation, and more general efforts to develop tools, practices, and structures for risk assessment and management.

(1) *Nuclear energy use.*

In the years following World War II, the fledgling fields of nuclear science and engineering turned their attention to peaceful uses of the atom, particularly electricity generation from nuclear energy. Public attitudes were generally quite positive, and nuclear power pioneers dreamed of "energy too cheap to meter." By the 1970s, however, local opposition to the construction of new nuclear power plants in the U.S. had emerged, eventually reaching majority opposition to this technology across the nation. Not a single plant was ordered in the U.S. after 1978, and every plant ordered after 1974 was eventually canceled, so that not a single reactor built in the U.S. was ordered after 1973. What lessons can we learn from this experience?

Research literatures on social/public perceptions of nuclear energy acceptance issues are considerable, especially from the years after the Three Mile Island incident on March 28, 1979, and the Chernobyl explosion on April 26, 1986, but also, more recently, focused on nuclear proliferation concerns. Examples of the many reports, often based in part on opinion surveys, include Freudenburg and Rosa, 1984; Rosa and Dunlap, 1994; and Rosa, 2001.

These literatures suggest at least two possible explanations for the growing public concern. One has been that nuclear technology has always been shrouded with, if not doomsday imagery, at least an imagery of some dread (Weart, 1982; Rosa, 2001), tapping into underlying public uneasiness about risks in human manipulation of the atom, publicity during the 1950s about a danger of nuclear war created an impression that anything nuclear might represent a threat to life as we know it (e.g., Weart, 1982), and above-ground testing of atomic weapons and concern for radioactive fallout could only have crystallized those images. In this view, with the signing of the test ban treaties and other actions addressing these issues, dread found a new object—commercial nuclear energy. The other explanation is simply that growing recognitions of risks associated with nuclear power plant operation and the nuclear fuel cycle led to a rational response to perceived risks, which was to slow down development until concerns about risks could be addressed. Evidence tends to support the latter (Mitchell, 1984), but the former may also contribute to special attention to nuclear power risks (see Viklund, 2004).

Generic lessons that some writers have drawn from this experience to include the following;

- Emerging technologies that are perceived as risking **large-scale catastrophe** tend to be treated differently from emerging technologies whose impacts are less visible or appear to be less profound.

- While scientists tend to focus on distinguishing between substantial vs. very small risks, the public tends to focus on **zero risks** vs. non-zero risks.

-While scientists tend to focus on the probability a risk will be realized, the public tends to focus on the **consequences**.

- **Large-scale** technology applications are more likely to cause public concern than small-scale applications (Wilbanks, 1984).

- An important aspect of risk estimation is "**human factors**," for example, in the operation of technology, not just technology characteristics and performance in the abstract.

- Public concerns are related to the extent to which a possible consequence of technological development and use is **unknown** vs. consequences based on evidence-based knowledge.

- Where technologies involving advanced science are developed in ways that present obstacles to **public participation**, relatively-uninformed public attitudes are more likely to impede than promote progress.

- Public concerns are conditioned by institutional factors, particularly public confidence and **trust** in institutions responsible for risk management.

In many cases, where scientific analysts saw little reason for concern but the public remained concerned, the public has been right and science has been wrong. A classic example was the advice offered to sheep farmers in Cumbria, England after the Chernobyl nuclear reactor accident, that they could easily protect their flocks from grazing on radioactive grass by keeping them out of the valleys. The farmers, but not the scientists, recognized that this solution was impractical because the pastures were not fenced (Wynne, 1989).

(2) *Radioactive waste management*

Related to both nuclear energy use and nuclear weapon production, radioactive waste management (mainly concerned with spent nuclear fuel and other radioactive wastes associated with nuclear power production) has been a matter of concern for at least half a century (e.g., NRC, 1957, 1984, 1990, 1994a, 2000, 2001, 2003). Geological disposal was initially recommended; and it continues to be judged scientifically sound and technologically feasible, although not without controversy (Winograd and Roseboom, 2008). Yet there is no social consensus about an acceptable approach for such waste disposal over the long term (e.g., Duncan, 2003; Greenberg et al., 2007a and b), and the nation continues to maintain the wastes (currently 60,000 metric tons) in temporary storage, generally close to where they are produced.

Increasingly, experts have concluded that the biggest challenges to waste disposition programs are societal in nature (e.g., Slovic et al.., 1979; Dunlap, Kraft, and Rosa, 1993; Rosa and Freudenburg, 1993; NRC, 2001). According to the NRC Board on Radioactive Waste Management (2001:30), "Most countries have made major changes in their approach to waste disposition to address the recognized societal challenges. Such changes include initiating decision processes that maintain choice and that are open, transparent, and collaborative with independent scientists, critics, and the public." What had once been considered a technical problem came eventually to be recognized as one of societal risk management (e.g., Wolfe and Bjornstad, 2003), and responsible agencies have begun to develop an experiential base of management strategies.

This body of research added generic lessons to those learned from public reactions to commercial nuclear power more generally. Some of the additional lessons learned include:

- Judgments about hazards often **differ** between the public and the technical community, and regardless of whose judgments are better, public perceptions matter in technology acceptance.

- Public judgments of the seriousness of hazards are related to the extent to which a possible consequence is dreaded, especially if the consequence is potentially **unbounded** in its effects.

- The same risks are considered to be more serious by **some** population segments than others; e.g., in general, white, male, affluent, and/or highly-educated people see radioactive waste as less risky than other people do.

- **Public participation** is often an effective way to promote public confidence in both institutions and technologies.

(3) *DNA Manipulation*

Manipulation of DNA has also raised serious issues of adaptive management of risks. When the first reports of gene splicing technology appeared, the scientific community quickly raised concerns that this technology might deliberately or inadvertently be used to create organisms with increased virulence or other novel characteristics. These possibilities eventually led to the 1975 Asilomar Conference, where scientists gathered to discuss the safety of manipulating DNA from different species (Barinaga 2000; Singer, 2001). The meeting, which focused only on accidental creation of recombinant organisms with dangerous properties, resulted in the NIH issuing guidelines in 1976 that regulated the conduct of recombinant DNA research and reviewed proposed experiments in this field. That system has evolved over time and remains in use today. In the same vein, following concerns in the scientific community about potential risks from breakthroughs in research, the NIH Human Genome Project created the Ethical, Legal and Social Implications Research Program to explore a set of "grand challenges" for genomic research related to ethical, legal, and social issues. A serious recent risk management challenge is the concern that advances in the life sciences could produce knowledge, tools, or techniques that could be deliberately misused for terrorism or new types of biological weapons (NRC, 2004a, 2004b; 2006b; WHO 2005; OECD 2004).

Lessons from this experience include the following (Barinaga, 2000: Singer, 2001):

- Risk assessment is not a scientific issue alone; it is also a **social issue**.

- Risks should be analyzed and assessed not only as scientists view them but also as **society** is likely to **view** them.

- It is easier to discuss risk issues before they become **chronic** and positions become hardened.

- In many cases, risk assessment needs to be **case-specific**, not generic, because possible consequences may depend on relatively subtle differences in substance composition and/or use.

(4) *Risk assessment and management.*

A large body of primarily inductive work has also been done on the broader class of technology management issues, typically collected under the topical heading of risk assessment and management (much of this has been reviewed in NRC, 1983, 1989, 1994b, 1996). These studies deal with a variety of hazards, mainly defined by the regulatory authorities of environmental and natural resource protection agencies. The trajectory of the NRC reports tracks a major development in this field, in which experts have increasingly recognized the need to supplement scientific analysis of risks with methods for integrating input from "interested and affected parties" (NRC, 1996:3), not only for managing the risks, but even for understanding them.

These bodies of work on risks related to specific technologies have dealt with potential impacts at all levels from the local to the international. And they have addressed many types of risks, including ecological impacts, public health threats, potential damage to the atmosphere and oceans, and the threats posed by nuclear and biological weapons, proliferation, and illicit international trade in potential biological and radiological weapons (NRC 1994c, 1995, 1997a, 1997b, 2006d, 2006e). The NRC reports and the many empirical sources on which they are based provide a valuable source of insight into the functions that must be performed to guide an emerging technology to successful implementation. From them can be derived a fruitful variety of empirically based propositions about ways to design management systems to perform those functions.

Further examination of evidence from past experience should permit a refinement of this list of functions and generate a working list of design principles for societal deliberation and decision making about emerging technology. The notion of design principles is already well developed in research on common-pool resource management (e.g., Ostrom, 1990; Agrawal, 2001, 2002; Stern et al., 2002a, 2002b; Dietz et al., 2003). However, the notion has yet to be transported to the area of managing technological development. Some of the design principles emerging from the commons research that may be relevant to the proposed activity include establishing low-cost mechanisms for conflict resolution, involving interested parties in discussing decision rules, allocating authority to allow for adaptation and change, and employing mixtures of institutional types (e.g., combinations of regulatory, market-oriented, and voluntary approaches).

The challenge of transporting knowledge from risk management to research has several elements: identifying the functions that must be performed in managing risks, identifying the relevant organizations and other actors (creating new ones if necessary), clarifying actor roles, and developing the rules under which actors influence decisions that guide the development and use of emerging technologies. The actors are likely to include government bodies, scientific organizations, markets, private-sector organizations, and other organizations and individuals. The rules and enforcement mechanisms may vary widely, and could involve national laws and regulations, market processes, international treaties and agreements, adoption of formal decision-making procedures, codes of conduct for scientists, and a variety of informal practices. The most effective mechanisms may vary by context or situation. In fact, the benefits of institutional variety and adaptability may be a highlight of the lessons of past experience.

Generic lessons from this body of experience echo many of the lessons above and are considered in greater detail in the section below that deductively develops insights from knowledge bases of social processes. For example, experience shows that "risk amplification"—the process by which risks come to be seen as larger or smaller—is fundamentally a social process (e.g., Pidgeon, Kasperson, and Slovic, 2003); that risk communication, including the roles of the media, is critically important in this process; and that "institutional permeability" is important to avoiding traps associated with overly narrow assumptions about risk. We can deduce the operation of these processes across a variety of S&T contexts, including bioenergy technologies.

EXPERIENCE WITH EMERGING TECHNOLOGIES

Other insights from experience are arising from new breakthroughs in such fields as nanoscience, bioscience and technology, and information science and technology. For example, the emerging field of toxicogenomics makes it possible, among other things, to prevent illness in individuals whose genes make them susceptible to adverse reactions to certain chemicals; it also makes it possible to engage in employment discrimination based on the same genetic susceptibility. The range of emerging societal issues is only beginning to be recognized and examined (e.g., Marchant, 2003a, 2003b). Synthetic biology, which uses engineering approaches to construct gene sequences and "new biological parts, devices, and systems…for useful purposes" (definitional statement at http://syntheticbiology.org), has the potential to create whole new organisms with as-yet unknown effects on ecological systems that are critical to human well-being. Examining early experience with these newer breakthroughs can be useful for inducing insights and refining the lessons learned from efforts to manage risks associated with earlier breakthroughs to apply to the emergent breakthroughs.

(1) *Nanotechnology*

Nanotechnology is a breakthrough field in which early experiences and knowledge bases can help in making sense of lessons from past experience. In many cases, the social acceptance issues are likely to be associated with "nano-bio" interactions, especially for human health (e.g., Kuzma, 2007): i.e., relationships between nanotechnology developments and biological systems, such as the potential that nano-technologies might be developed that would cure health problems such as clogged arteries or cancer or Alzheimer's disease. Science fiction has speculated about such effects for many decades, imagining such possibilities as computer-designed "cocktails" that would enable a consumer to change his/her physical characteristics on demand (at a cost). There is a significant chance that, as nano-science develops, public concerns about what might be considered potential misuses of nano-biology could emerge much as they have for other aspects of bioengineering (e.g., efforts by the Saddam Husseins of 2050 to engineer "perfect warriors," or limiting access to the fruits of technology development to the wealthiest individuals).

Examples of potential nano-biology applications related to human health include DNA molecular and protein engineering (a way to deploy genetic-engineering breakthroughs), targeted drug delivery, molecular motors, preventive maintenance of body systems, and photodynamic therapy. In addition, some technology potentials with health-related applications also have workplace implications. One instance is neuro-electronic interfaces (nerves linked to computers), which could be applied to overcoming paralysis or to enhancing work performance (e.g., in astronauts). Issues are likely to include tradeoffs between perceived benefits and risks (Cobb, 2005), the level of trust in institutions responsible for determining and managing risks (Rosa and Clark, 1999; Siegrist et al., 2007a and b), and roles of the media in framing or even stigmatizing technologies by how risks are communicated (Gregory et al., 2001).

One example of a risk management issue is that nanoparticles can have very different biological properties (e.g., toxicity) than larger-sized particles of the same chemical composition. A result is that regulations based on exposure levels might have very different consequences if the exposure is to nanoparticles rather than the larger particles to which regulation is usually applied (e.g., NRC, 2005a). More research on environmental, health, and safety effects has been recommended (NRC, 2006c), but the implications for societal management are only beginning to be recognized and seriously considered. For further information, see the nanotechnology part of the DOE ELSI program, along with other such activities as http://www.nanotechproject.org/.*Genetic engineering.*

(2) *Biotechnology.*

A direct extension of advances in the science and technology of DNA manipulation (see above) is the rapidly emerging field of genetic engineering: modifying existing genes and/or proteins or developing new ones for particular purposes. Agronomists and other life scientists have been engineering plant and animal species for centuries by selective breeding and hybridization, from blue roses to new species of wheat and corn. Hence, genetic manipulation of plants or animals to achieve desired products is not an entirely new nor unfamiliar idea. What is different is that the selective breeding in the past was based upon the distribution of morphological features of plants and animals, not on the underlying genetic structure of those features. Manipulation at the genetic level may pose two new types of undesirable risks: (a) it may be used for socially undesirable purposes, e.g., designing substances for bio-terrorism, or (b) it may be used for acceptable purposes but have unacceptable consequences, e.g., unintended gene transfers. Early experience with DNA manipulation, for instance from agriculture, animal science, and medical science, suggests that they could generate some social concerns similar to those that arose from manipulations of the atom. Among the concerns could be what defines a human being and what should be the civic role of genetically or chemically modified humans (Stehr, 2004). The manipulation of fundamental structures of matter, whether animate or inanimate, easily evokes dreaded or catastrophic imagery in people (Weart, 1982; Rosa, 2004).

Genetically modified foods are an especially salient case in point. Countries and regions of the world have tended to differ in their acceptance of risks associated with "novel traits" (Andree, 2002), with Europe generally more precautionary about modified foods than North America. Risk communication, particularly media portrayals, has received considerable research attention as a factor (Gorke and Ruhrmann, 2003; Bonfadelli, 2005; Gutteling, 2005; Lewison, 2007; Marks et al., 2007; McInerney, 2004); consistent findings have been elusive, however. Labeling practices can also affect consumer acceptance (Cardello et al., 2007). Another factor is perceptions of benefits as well as risks (Gaskell et al., 2004). Ambivalence tends to be greater where available information is limited (Cunningham, 2006) or where public trust in responsible institutions is in question (Larrere, 2003; Durant and Legge, 2005; Bruce, 2002; Priest, 2003; but also see Frewer et al., 2003).

Along with issues related to genetic engineering within established management systems, another set of emerging issues concerns uses of genetic engineering knowledge outside those systems. One example is animal cloning, which has been shown to be biologically feasible in at least some species. The technique appears to be growing in acceptance in a few connections, such as for dairy cattle and mules, while most people judge it entirely unacceptable in the case of humans.

(3) Information science and technology.

Information and computing science and technology are affecting both social institutions and the collection, distillation, and sharing of knowledge in ways that are not well understood. For example, these developments – which, by standards of historical experience, have emerged with astonishing rapidity – are transforming management/organizational communication and control systems, from worldwide e-mail to cybersecurity. Technological change has revolutionized how we relate to each other -- how we exchange messages and materials, how we establish or refine our social identities, and how we align our interests with distant, unknown strangers, encouraging and accelerating many kinds of interaction. A question yet to be answered is about the changing role of face-to-face interaction in an era of global information technology.

These developments may raise concerns about social behavior and social relations. Available evidence suggest that in most cases the level of concern is not yet alarming. But more fundamental societal issues—such as about the boundaries between public and private space -- may yet emerge. Other concerns include intellectual property rights, privacy (e.g., Bonner, 2007; Trudel, 2006), information security (Dourish and Anderson, 2006), and the restriction of access to certain types of information for segments of the public (e.g. keeping pornography from minors).

Information technology affects life in other ways as well. One vivid example is how new information technology has made it possible for people with mobile skills to make a living in rather remote locations (Robb and Riebsame, 1997). Another example is the growing attraction of electronic recreational alternatives within the household in contrast to more conventional recreational activities outside the household, especially for many young people.

Less familiar but profoundly important are the potential impacts, both positive and negative, of modern information and communication technologies on democratic institutions. These technologies offer new ways to access and monitor government services and to engage directly in political activities. Issues that deserve more research attention include equity in access to these opportunities, whether they lead to more informed voters, whether they are likely to make democratic decision-making more or less consensual and integrated, and the degree to which the impacts are likely to differ according to political and cultural context. The same technology can be used undermine democratic processes by spam slams or by sending viruses to the websites of political opponents.

Looking to the future, a significant question is how the growing use of largely aspatial information and communication technologies change the meaning of location and how we interact and arrange our activities in space (Wilbanks, 2003). What will be the continuing value of physical proximity, of personal contact and communication, and of social interactions and groupings? How will these aspects of life be modified and cultures changed by new technologies and how we use them? How will they modify political cultures and affect access to political processes? To what extent will communication techniques reduce demand for travel and thereby, demand for fossil fuels? Information technology is also revolutionizing how information is collected, analyzed, and communicated to a wide variety of audiences from classrooms to the general public. The revolution, in no small way, is a direct result of federal government funding not only for information collection and research but for the origins of such powerful tools as the Internet and e-mail. New developments are raising concerns that by providing access to financial resources, specialized hardware and software, and complex databases, the new technologies give parties endowed with these assets advantages that others may find difficult to overcome.

3. DEDUCTIONS FROM KNOWLEDGE OF BASIC SOCIAL PROCESSES

Much of the societal concern about emerging technologies stems from the possibility that when developed for specific public or private purposes, they may have negative effects on broader public goods that lie outside the concern or the control of those developing and deploying the technologies. It thus seems that areas of basic social science research that address this generic problem can yield insights that are potentially relevant for the governance problems posed by breakthroughs in science and technology. This section discusses the implications of several research areas that have such a focus, and of basic research on the development and use of decision-relevant scientific information, for the case of decisions about emerging technologies.

PERCEPTION, ASSESSMENT, AND MANAGEMENT OF SOCIETAL RISKS

A major research tradition in the social and behavioral sciences frames decisions about technologies in terms of risk assessment and risk management (e.g., National Research Council, 1983, 1994a,b, 1996, 2006a; Lofstedt and Frewer, 1998; Jaeger et al., 2001; Pidgeon et al., 2003; Renn, 2008). Much of this research is concerned with the control or management of risks to the public created by the actions of individuals or organizations, such as releases of toxic chemicals, of radioactive materials, or of pathogens that create public health and ecological hazards. Initially, this line of research emphasized techniques for the scientific assessment of the possible negative consequences of the production of hazardous substances and processes. Risk, in its usual framing, is the weighting of these consequences by the probabilities of their occurrence. Such quantitative risk assessments are normally handled by regulatory authorities, which employ technical analysts to conduct the assessments and use a command-and-control style of governance to achieve regulatory objectives.

An important insight from research on risk is that risks and hazards vary qualitatively in ways that make a major difference to people who may be exposed to the hazards. For example, hazards that are perceived as uncontrollable, or that evoke emotional reactions of dread (e.g., terrorist attack) cause greater concern than other hazards that may pose an equal or greater mathematical probability of loss of life or limb (e.g., Slovic et al., 1980; Slovic, 1987; Gould et al., 1988). In contrast with the importance of these and other qualitative factors to the parties potentially affected by risks, traditional risk assessments usually summarize risks in terms of a single metric (e.g., life-years lost, financial cost-benefit ratio), often failing to address completely other aspects of the risk in their calculations. A related insight from research is that different parties to a risk decision have different concerns and values, as well as different, sometimes incompatible, ways of understanding or framing the decision situation (e.g., National Research Council, 1996). Consequently, risk analyses are often focused on scientific questions that, for some of the parties, are beside the point. A good example was a risk assessment for a soil decontamination plant proposed for siting in Chester, Pennsylvania, a declining industrial city populated largely by low-income African-Americans (National Research Council, 1996). The proposal was to assess the incremental health risks to the exposed population. Community representatives countered that adding another source of toxic exposures in a city that already had several was unfair, and ultimately a different risk assessment was done that examined risks throughout the city and the surrounding area and that estimated cumulative risk to people living near various possible sites. This broadened the question from whether to site in Chester to whether to site in Chester versus more affluent nearby communities where people's preexisting exposure was low. The literature was summarized in a recent National Research Council (2005:26) report as follows: "when science is gathered to inform environmental decisions, it is often not the right science. Among the consequences are heightened social conflict, delayed decisions, and mistrust" (see also Fischhoff, 1989).

Recognition of the multidimensional nature of risk and the existence of competing values and framings has led to many calls for approaches to risk analysis that distinguish and then integrate two classes of information—about phenomena and their consequences, and about values (e.g., Payne et al., 1993; National Research Council, 1996; Hammond et al., 1999). Decision science has developed some systematic techniques for structuring individuals' thinking and groups' deliberation about choices, including tradeoffs among values and objectives, that can be applied to analyzing the risks from emerging technologies (e.g., Slovic and Gregory, 1999; Gregory and McDaniels, 2005). A basic strategy is to consider each kind of consequence associated with a technology separately, so that each affected party can integrate across the consequences in terms of its own values and concerns, and then to encourage consideration of the consequences and tradeoffs in a structured format. Analysts have advocated that such analytic-deliberative processes be organized in ways that involve the full spectrum of interested and affected parties (e.g., Renn et al., 1995; National Research Council, 1996).

These insights from risk research strongly apply to decisions about emerging technologies, which are likely to score highly on a set of characteristics that have been identified as making it advisable to use analytic-deliberative processes: complexity of choices, multidimensionality of risk, scientific uncertainty, value conflict and uncertainty, long-time horizons, difficulty of excluding actors from taking action, high stakes, potential for mistrust, and time pressure (Dietz and Stern, 1998; National Research Council, 2005). Moreover, as new technologies are developed and deployed, unanticipated hazards sometimes emerge, making iteration and separate consideration of risks even more important.

The problem of emerging technologies extends the usual subject matter of risk research into territory in which standard risk analytic techniques have limited value because not only the probabilities of hazards, but because the nature of the hazards themselves may be unknown or, in some cases, unknowable until they are realized. Risk analytic techniques such as fault-tree analysis can estimate the probabilities of hazards being realized through various pathways, so that total risk can be calculated and the best risk-reduction targets (critical paths) can be identified. However, such approaches are much less useful if the critical paths are not foreseen. This situation can easily arise when new technologies alter ecological systems about which science lacks predictive understanding. Broadly inclusive deliberative processes can consider the unknowns more easily than quantitative, analytical approaches. They may also be able to generate new ways of framing a decision problem, and perhaps new solutions, which may not occur to risk analysts acting alone.

Emerging technologies also stretch the usual risk framework in that societal management issues often cannot be resolved within the national-level regulatory institutions that are the usual users of risk assessments. Some technologies fall outside the authority of existing regulatory bodies (e.g., U.S. laws that exempt substances produced in quantities that fall below a weight or volume threshold cannot effectively regulate nanotechnology). Many are global in application, so that technology developers and implementers can sometimes escape regulatory authority by moving across national boundaries.

Given the limited enforcement powers of most national institutions for new technologies that appear in global markets, the problems call for alternatives to command and control, including creative solutions that rely on combining various forms of influence, such as agreed norms, voluntary enforcement agreements, and created markets, along with the regulatory approaches that are the most common policy focus in risk research. In recent years, thinking about environmental management has paid increasing attention to such approaches (e.g., National Research Council, 2002a, 2002d; Prakash and Potoski, 2006). Some hypotheses about when and how best to combine these approaches can be drawn from the research on common-pool resource management and on global policy networks, discussed in the two next sections.

COMMON-POOL RESOURCE MANAGEMENT

Research on common-pool resource (CPR) management (e.g., Hardin, 1968; McCay and Acheson, 1987; Ostrom, 1990; Baland and Platteau, 1996; National Research Council, 2002a) focuses on institutions for managing private use of public goods, most typically resources that are depletable by extraction, such as forests (Gibson et al., 2000), fisheries (e.g., Acheson, 1981; Berkes et al., 2001), and irrigation water supplies (e.g., Wade, 1988; Bardhan and Dayton-Johnson, 2002); the usual focus is on the prevention of damage to public goods by private appropriators. In a sense, this line of research begins with a problem opposite of the risk assessment problem, in the sense that risk assessments typically concern negative public consequences of things added to the environment, whereas CPR research typically concerns things removed from the environment. Both lines of research, however, focus on negative public consequences of private actions.

Research in the CPR tradition pays special attention to the roles of community-organized and other non-governmental institutions, typically created by the appropriators to establish and enforce management rules, which operate between the market and the state. However, it also considers the roles of markets and government organizations. A major contribution of this research has been to increase attention paid to institutions, particularly non-governmental governance institutions; another has been to highlight the importance of relationships among institutions, particularly among those operating at different scales (e.g., Berkes, 2002; Young, 2002). This extensive body of research has led to the identification of several generic governance challenges and design principles that management systems must meet to prevent the destruction of public goods (Ostrom, 1990; Stern et al., 2002a, 2002b; NRC, 2002a; Dietz et al., 2003).

A short list of governance requirements for common pool resources (Stern et al., 2002a, 2002b; Dietz et al., 2003), slightly adapted, seems applicable to emerging technologies:

- Provide timely, understandable information about the technology and human interactions with it, matched to the scale of decision making and with accountability for the information providers;
- Deal with conflicts about the development and use of the technology;
- Induce compliance with rules at low cost;
- Provide needed infrastructure, particularly institutional infrastructure; and
- Encourage adaptation and change.

Three general principles for governance institutions have been identified as especially relevant for meeting these requirements in the case of global-scale problems (Dietz et al., 2003). These can be considered as embodying a set of working hypotheses about effective strategies for governing emerging technologies.

(1) Analytic-deliberative process. Well-structured dialogue involving scientists, technology developers, and interested publics, and informed by analysis of key information about the technology and its use and effects, and iterated over time, appears critical (NRC, 1996; Dietz and Stern, 1998; Mitchell et al., 2006). Such dialogue provides improved information and shared understanding, a venue for dealing with conflicts well enough to produce consensus on governance processes and rules, and a mechanism for orderly adaptation and change. For governing emerging technologies, it makes sense to reconvene dialogues at different phases of research, development, demonstration, and application, as well as when important new information appears about the technology's uses and potential consequences.

(2) Nested governance at levels from local to global. Centralized control is often impossible for technologies that can be deployed anywhere on Earth, and when tried, it has had a poor record, especially for monitoring and controlling local actions and setting appropriate limits that encourage compliance. An important issue with emerging technologies is to coordinate the technology developers, who usually have the best knowledge of local developments with the technology and may have some informal influence over each other, and governmental authorities at various levels that can set objectives for control in the public interest.

(3) Institutional variety. Successful management is more likely when governance relies on mixtures of institutional types (e.g., hierarchies, markets, and community self-governance) that

employ a variety of decision rules to change incentives, increase information, monitor use, and induce compliance. Innovative rule evaders can have more trouble with a multiplicity of rules than with a single type of rule (Gardner and Stern, 1996; National Research Council, 2002a, 2002b).

The problems raised by emerging technologies extend beyond the usual range of common-pool resource management research in that the benefits and risks are typically global, the affected parties are geographically scattered, and the management problem concerns the creation of public hazards rather than the depletion of public goods. These differences suggest that the theoretical paradigm may require modifications to be fully applicable. Nevertheless, its hypotheses deserve careful consideration.

INTERNATIONAL INSTITUTIONS AND NETWORKS

The increasingly globalized nature of science and technology (S&T) research, of the legal and illegal markets for breakthrough products, and of the potential for their intentional misuse makes basic social science knowledge about international governance increasingly relevant to societal management of S&T. Research on international governance includes work on international regimes that link national governments through various organizations (e.g., Keohane and Nye, 1972, 1998, Hasenclever et al., 2000, Specter and Zartman, 2003, Krasner, 1983) and more recently on international networks of governance (Buchanan and Keohane, 2006, Slaughter, 2004; Reinicke, 1998; Reinicke and Deng, 2000; Rischard, 2002).

The work on regimes provides guidance for resolving global problems in situations of interdependence, drawing initially in large measure on the development of international financial institutions. Very generally, the regimes literature focuses on a core international agreement or institution and the variety of ancillary formal and informal mechanisms that grow up around that core to manage a key problem. In the area of S&T, treaties that attempt to limit the proliferation of nuclear, chemical, and biological weapons provide exemplars of international efforts to limit access to knowledge or equipment that enable the acquisition of weapons capabilities. The Montreal Protocol on substances that harm the atmospheric ozone layer is an example of a regime aimed at restricting uses of technology that has been an object of research (Haas, 1992a; Litfin, 1994). International institutions for trading pollution allowances (Tietenberg, 2002) are a newer example.

The research focus on networks responds to a highly decentralized world, in which multiple institutions from the governmental, corporate, and "civil society" sectors with roughly equal stature and claims on the issue and a range of "stakeholders" need to be involved in decision-making. Research on networks draws heavily on cases in international finance and environmental protection: of the 21 case studies that provided the basis for the recommendations in Reinicke and Deng (2000), most dealt with environmental or economic issues and none dealt with managing advances in science and technology. Work on the roles of "epistemic communities" in global environmental regulation (e.g., Haas, 1989, 1992a, 1992b; Haas et al., 1993) led to a continuing research interest in institutions at the international level in which scientists are involved in an adaptive management process. Growing recognition of the need to address the global challenges of breakthroughs in science and technology (S&T) is exemplified by a series of reports from the NRC (NRC, 2004a, 2004b; 2006) and from international organizations (e.g., WHO, 2005; OECD, 2004) with interests in ensuring that the advances in life sciences and technology are available to promote human wellbeing while simultaneously reducing the risks of deliberate or inadvertent misuse. Scholarly research on international governance can help provide insights for addressing these issues.

What have been called "global public policy networks" (Reinicke and Deng, 2000) act alongside, but not as part of governments and international organizations, and can perform several functions: putting issues on the policy agenda, negotiating and setting global standards, gathering and disseminating knowledge, creating and improving markets, helping to implement international agreements, and improving participation of those needed to fulfill the other functions. All these functions are likely to be important for governing emerging technologies, and extra-governmental networks may be required because most of these technologies have the potential to be deployed anywhere in the world. Research on global policy networks offers some insight on the creation and nurture of networks that might be useful for emerging technologies. For example, Reinicke and Deng's (2000) review concludes that those who wish to promote such networks must get the right people on board; create a shared vision; make sure the participants recognize their need for collective thinking to solve the problem at hand; keep the process moving by setting achievable milestones; secure adequate funding; maintain some structure while avoiding bureaucratization; find allies outside the sector; and tackle the problems of including both local and global actors, and the developed and developing worlds. This line of research offers some more detailed advice on how to do these things, which could probably be adapted to suggest approaches applicable to specific emerging technologies.

SCIENCE COMMUNICATION AND UTILIZATION

Research on how decision makers and societal systems respond to new knowledge can provide insights into the governance of emerging technology. For example, research on "science utilization," focused largely on government agencies as users, indicates that decision-relevant scientific information is not necessarily used, even when it is made available to those who can benefit from it and even, as, with government officials, when it is their responsibility to make decisions on the basis of the best available information (e.g., Sabatier, 1978; Weiss and Bucuvalas, 1980; Freudenburg, 1989; Landry et al., 2003; Romsdahl, 2005). Similar conclusions emerge from research on environmental communication (e.g., McKenzie-Mohr and Smith, 1999; Schultz, 2001), disaster communication (e.g., Mileti, 1999; National Research Council, 2006a), public health communication (e.g., Valente and Schuster, 2002), risk perception and communication (e.g., National Research Council, 1989; Fischhoff, 1989; Slovic, 2000, Pidgeon, Kasperson, and Slovic, 2003), and the use of information from climate forecasts (e.g., National Research Council, 1999, 2008).

These bodies of research begin from a shared problem formulation: that science can contribute valuable information to nonscientists, but that the needed information is not optimally provided or used. The problem is sometimes framed in terms of the relationship between the supply and demand for science (Sarewitz and Pielke, 2007). Various explanations of the non-use of information receive support in the research, including cognitive limitations of the potential users, the extra effort needed to use new information ("translating" the information, altering decision routines); inadequate communication between information producers and users, and scientific research agendas that are shaped more by the scientists' intellectual curiosity than by users' information needs and that result in information that users do not see as decision relevant (e.g., Clark and Majone, 1985; National Research Council, 1984b, 1989, 1999, 2002d; Cash et al., 2003; McNie, 2007).

Effective use of information has often been found to depend on the efforts of intermediaries or "boundary organizations", which function as central nodes in what are sometimes called knowledge-action networks (Cash et al., 2003; van Kerkhoff and Lebel, 2006). These intermediaries can help scientists understand which information would be most useful to decision makers; develop tools and techniques for making such information, once available, intelligible and accessible to users; and provide a credible source of "translated" information for their constituencies. Studies of the use of information from climate forecasts indicate that enhanced creation of such networks is a high priority for getting a new kind of decision-relevant knowledge produced and used (National Research Council, 1999, 2008).

The problem frame used in this literature is probably relevant to important aspects of the governance of emerging technology. For example, information about the risks of new technologies and about effective governance strategies may not be used for many of the same reasons other scientific information often goes unused. Research on science utilization and in related fields identifies several key factors that can determine whether or not decision makers seek and use scientific information: the existence of good communication links between information providers and users, the degree to which information is easily incorporated into users' decision routines, the credibility of the information providers from the users' perspective, the strength of communication networks among the information users, and the potential for decisions to be challenged. These research conclusions implicitly identify a set of challenges that management systems must meet if they are to make best use of available information about the possible downsides of S&T breakthroughs, including its risks.

It is important to note that the science communication framework, with its emphasis on information that goes unused, may not apply well to information about the opportunities that new technologies present. Potential gains from a technology may strongly motivate potential users to seek out and emphasize information about the opportunities it presents while ignoring unexpected (and undesired) outcomes. The main governance problem may arise from overly enthusiastic development and use without adequate consideration of information about the risks—or in the case of malevolent actors, use *because* of information about the risks.

4. SUMMARY

This report has summarized a number of insights from both experience and theory about societal responses to emerging technologies that may be perceived as involving risks. Among the insights are that technology acceptance is fundamentally a social process, not a scientific process; that societal concerns tend to focus on non-zero vs. zero risks of large-scale catastrophic unintended consequences; that social impediments are less likely to arise if risk communication occurs earlier rather than later and that building trust in institutions by promoting public participation increases the likelihood that a new technology will be acceptable. These insights are worth considering as bioengineering for energy production moves forward, in order to reduce chances that scientifically promising strategies will provoke serious social concerns rather than public acceptance.

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