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Real-time technology assessment

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Abstract

Social science scholarship has identified complex linkages between society and science, but it has been less successful at actually enhancing those linkages in ways that can add to the value and capability of each sector. We propose a research program to integrate natural science and engineering investigations with social science and policy research from the outset — what we call "real-time technology assessment" (real-time TA). Comprising investigations into analogical case studies, research program mapping, communication and early warning, and technology assessment and choice, real-time TA can inform and support natural science and engineering research, and it can provide an explicit mechanism for observing, critiquing, and influencing social values as they become embedded in innovations. After placing real-time TA in the context of scholarship on technology assessment, the paper elaborates on this coordinated set of research tasks, using the example of nano-scale science and engineering (nanotechnology) research. The paper then discusses issues in the implementation of real-time TA and concludes that the adoption of real-time TA can significantly enhance the societal value of research-based innovation. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Scientific and technological innovation continually remakes society. Society reciprocally accommodates, manages, and redirects innovation. Social science scholarship has contributed to a broader and more nuanced understanding of this "co-production" of science and society in traditional scientific arenas such as laboratories,

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political arenas such as courtrooms, and hybrid arenas such as advisory committees and technology transfer and extension services.[1] Political economic studies of innovation pathways have elucidated the roles of organizational structure, consumer feedback, and various policy environments in this process.[2] But such scholarship has been less successful at actually enhancing linkages between innovation and societal action in ways that can add to the value and capability of each. An implicit societal demand for more sustained and pragmatic attention to strengthening such linkages can be seen in continuing public controversies over the societal implications of innovation, be it particular technologies such as nuclear power, genetically modified foods, cloned mammals, or genetic screening; or dilemmas raised by technological systems, such as the protection of privacy, the definition and protection of intellectual property, and the distribution of the benefits and costs of science and technology.

One limited way that federally funded research and development (R&D) programs address this linkage is by supporting research in the ethical, legal, and social implications (ELSI) of initiatives such as the Human Genome Project, information technology, and nanotechnology. Such work, however, has not been well-integrated into either the science policy process or the R&D process.[3] The necessary and logical next step to ELSI is integrating social science and policy research with natural science and engineering investigations from the outset[4] — what we call here “real-time technology assessment”. Such real-time TA can inform and support natural science and engineering research, and it can provide an explicit mechanism for observing, critiquing, and influencing social values as they become embedded in innovations.

This paper places our conception of real-time TA in the scholarship on technology assessment, which is a wide category encompassing an array of policy analytic, economic, ethical, and other social science research that attempts to anticipate how

[1] For the concept of co-production, see S. Jasanoff, Beyond Epistemology: Relativism and Engagement in the Politics of Science, Social Studies of Science 1996; 26(2): 393–418. On co-production in the courtroom, see S. Jasanoff, Science at the Bar (Cambridge: Harvard U. Press, 1995). For the technology transfer example, see D.H. Guston, Stabilizing the Boundary Between US Politics and Science: The Role of the Office of Technology Transfer as a Boundary Organization, Science, Technology, & Human Values, 1999;29(1):87–111. For examples of advice and extension, respectively, see C. Miller, Hybrid Management: Boundary Organizations, Science Policy, and Environmental Governance in the Climate Regime, Science, Technology, & Human Values 2001;26(4):478–500 and Cash D, “In Order to Aid in Diffusing Useful and Practical Information . . .”: Agricultural Extension and Boundary Organizations, Science, Technology, & Human Values, 2001;26(4) 478–500.

[2] See von Hippel E. The Sources of Innovation (New York: Oxford University Press, 1994); also S.J. Kline, and N. Rosenberg, An Overview of Innovation, in Landau R, Rosenberg N, eds, The Positive Sum Strategy (Washington, DC: National Academy Press, 1986). For the connection of the economic and technological development arguments to methodological issues in technology assessment, see A. Rip, Technology Assessment, in Smelser NJ, Bates PB, eds, International Encyclopedia of the Social and Behavioral Sciences, vol. 4.10 (New York: Elsevier, 2001).

[3] Hanna KE. The Ethical, Legal, and Social Implications Program of the National Center for Human Genome Research: A Missed Opportunity? in Bobby EM, Fineberg HV, Bulger RE, eds, Society’s Choices: Social and Ethical Decision Making in Biomedicine (Washington, DC: National Academy Press, 1995); and McCain L in this issue.

[4] Guston DH, Woodhouse EJ, Sarewitz D. A Science and Technology Policy Focus for the Bush Administration, Issues in Science and Technology (Spring 2001), 29–32.

research and research-based technologies will interact with social systems.[5] The paper also articulates a real-time TA agenda around the example of nanotechnology. We believe such a new technology assessment is an essential — perhaps the essential — component of a new science and technology policy. Without a robust capacity to conduct real-time TA, society will be unable to maximize the benefits of science-based innovation, minimize its risks, and ensure responsiveness to public interests and concerns.

2. Toward a new technology assessment

Claims to novelty in science and technology policy often anchor the *ancien regime* in Vannevar Bush's durable polemic, *Science, The Endless Frontier*.[6] For more than fifty years, its prominence has overshadowed the similar, but in many ways more thoughtful and rigorous, 1947 report by John R. Steelman, *Science and Public Policy*. Among the substantive differences between the Bush and Steelman reports was their treatment of the social sciences. Bush neglected social sciences, believing them unworthy of, or unripe for, federal patronage. Steelman, himself an economist, maintained that the social sciences should be part of the federal scheme of research support. More to the point, Steelman cited at the beginning of his report the suggestion "that competent social scientists should work hand in hand with the natural scientists, so that problems may be solved as they arise, and so that many of them may not arise in the first instance."[7] Over time, of course, the National Science Foundation that Bush's report helped establish rejected his vision of the social sciences. Instead, NSF included the social sciences as insular disciplines under its jurisdiction, and enlisted them as tools for monitoring the science enterprise — but not assessing societal implications.[8] Steelman's view of the collaboration of the social and natural sciences — real-time technology assessment *avant la lettre* — has not yet come to pass.[9]

The vision of technology assessment that did emerge was closer to "science pro-

[5] Technology assessment shares some lineage and characteristics with environmental assessment; both derive from a combination of intellectual and social movements of the 1960s and attempt to anticipate and ameliorate the down-side impacts of human interventions.

[6] Bush V. Science, The Endless Frontier (Washington, DC: National Science Foundation, 1950).

[7] This sentiment was initially expressed by a report of the National Research Council and adopted by Steelman in the preface of his report. J.R. Steelman, Science and Public Policy (Washington, DC: US Government Printing Office, 1947).

[8] Gieryn TF. Cultural Boundaries of Science: Credibility on the Line (Chicago: University of Chicago Press, 1999).

[9] The first inklings of technology assessment in the US government, however, seemed to have occurred in 1937 when both a Cabinet-level committee in the Executive branch and a committee of the House of Representatives called for mechanisms to consider the economic and social implications of technological progress. See Herdman RC and Jensen JE. The OTA Story: The Agency Perspective, Technological Forecasting & Social Change, 1997;54(2&3):131–144.

poses, society disposes",[10] in which the scrutiny of innovation was limited to advising society, or certain segments thereof, about how best to respond to the consequences of developing technologies and technological systems. It contained little of the anticipatory or preemptive functions that Steelman advocated, that the social movement for technology assessment voiced anew in the 1960s, and that was inscribed in the chartering legislation for the Office of Technology Assessment (OTA) of the US Congress.[11]

The fear of untoward political interference in the research and development (R& D) process no doubt played a role in the failure to apply fully the tools of social science to the problem of enhancing the societal benefits of science and technology.[12] But the reasons for this approach were — and remain — rooted in a central truth about the development and proliferation of technology in society: that this process is largely unpredictable, and thus not subject to anticipatory governance.

Nevertheless, the centrality of technology in society assured some attempts to enhance relevant decision-making capabilities. Two types of technology assessment evolved: an "instrumental" type in which the social scientific and policy analytic approaches of experts dominate; and a "discursive" type in which the lay-public participates in a more deliberative and educative process.[13] In either case, however, technology assessment as a practice became lodged in institutions advising national parliaments. Resulting organizational relations not only compounded the problem of "science proposes, society disposes" by regularly requiring a political trigger for the initiation of TA activities, but they also isolated TA from the R&D enterprise itself — causing technology assessment organizations to navigate, not always suc-

[10] Guston DH. Integrity, Responsibility, and Democracy in Science, SciPolicy: The Journal of Science and Health Policy, 2001;1(2):168–189.

[11] According to its charter (P.L. 94-484), OTA was to provide "early indications of the probable beneficial and adverse impacts of the applications of technology and to develop other coordinate information which may assist the Congress".

[12] Perhaps the most eloquent spokesman of this position was Michael Polanyi, who argued that "You can kill or mutilate the advance of science, [but] you cannot shape it". See Polanyi M. The Republic of Science: Its Political and Economic Theory, Minerva, 1962;1:54–73. For the related threat of "apraxia" — that complex technological society will fail to function should authority not be vested in experts alone — see Winner L. Autonomous Technology: Technics-Out-of-Control as a Theme in Political Thought (Cambridge: MIT Press, 1977).

[13] Vig NJ, Paschen H, eds, Parliaments and Technology: The Development of Technology Assessment in Europe (Albany: The State University of New York Press, 2000). The dichotomy is similar to that between a "policy analysis model" and a "public deliberation model" in Guston DH, Bimber B, Technology Assessment for the New Century, Working Paper #7, Edward J. Bloustein School of Planning and Public Policy, Rutgers University, New Brunswick, NJ. Available at http://policy.rutgers.edu/papers/7.pdf, and to the vision of participatory analysis in Laird F, Participatory Analysis, Democracy, and Technological Decision Making, Science, Technology, & Human Values, 1993;18(3):341–361. For more on the discursive mode, also see Renn O, Participative Technology Assessment: Meeting the Challenges of Uncertainty and Ambivalence, Futures Research Quarterly, 1999;15(3):81–97.

cessfully, between the Scylla of political irrelevance and the Charybdis of technical inadequacy.[14]

In the United States, OTA sailed these straits from 1974 to 1995. In the wake of its elimination by Congress, there is a great creative opportunity to revisit and reinvent technology assessment.[15] This opportunity exists organizationally, in the sense of creating a new technology assessment that is not centralized around Congress but instead widely distributed through a society that is increasingly integrated technologically.[16] (We do not argue, however, that Congress does not need an institution devoted to assisting it with responding to issues with high scientific and technological content.[17])

This opportunity also exists procedurally, in the sense of creating a new technology assessment that is not linked to a formal process of expert panels and report writing, congressional hearings and legislation. The institutions for technology assessment in Europe, which to some extent are intellectual progeny of OTA, can provide some guidance to the United States in this endeavor, as their later foundings meant they often embodied more contemporary societal relations and drew on more contemporary intellectual perspectives. (Indeed, even from its founding, OTA distanced itself from the intellectual underpinnings of technology assessment and technology forecasting.[18]) Particularly important among these perspectives is what has become known as "constructive technology assessment", developed in the 1980s and 1990s largely under the auspices of the Netherlands Office of Research on Aspects of Technology.[19]

Constructive technology assessment (CTA) is an attempt "to broaden the design of new technologies" through the "[f]eedback of TA activities into the actual construction of technology".[20] CTA has three particular analytical achievements: socio-technical mapping, which combines the stakeholder analysis of traditional TA with the systematic plotting of recent technical dynamics; early and controlled experimen-

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[14] Bimber B. The Politics of Expertise in Congress: The Rise and Fall of the Office of Technology Assessment (Albany: The State University of New York Press, 1996) and Guston DH, Bimber B, op. cit.

[15] La Porte TM. New Opportunities for Technology Assessment in the post-OTA world, Technological Forecasting & Social Change, 1997;54(2&3):199–214. See also a meeting organized by Morgan MG. Creating Institutional Arrangements to Provide Science and Technology Advice to the US Congress, a workshop held in Washington, DC (14 June 2001) and Time for a Bipartisan OTA, Nature (10 May 2001), 117.

[16] Such organizations can serve as the "honest brokers," many of which are necessary for the connection of research to human needs. See Sarewitz D. Frontiers of Illusion: Science, Technology, and the Politics of Progress (Philadelphia, Temple University Press, 1996).

[17] See Chubin DE. Filling the Policy Vacuum Created by OTA's Demise, Issues in Science and Technology, 2000-01:Winter:31–32.

[18] See Coates V. Technology Forecasting and Assessment in the United States: Statistics and Prospects, Futures Research Quarterly, 1999;15(3):5–25.

[19] van Eijndhoven J. The Netherlands: Technology Assessment from Academically Oriented Analyses to Support of Public Debate, pp. 147–172 in Vig N, Paschen H, op. cit.; Schot J, Rip A, The Past and Future of Constructive Technology Assessment, Technological Forecasting & Social Change, 1997;54(2&3):251–268.

[20] Schot J, Rip A, op. cit., p. 252.

tation, through which unanticipated impacts can be identified and, if needed, ameliorated; and dialogue between innovators and the public, to articulate the demand side of technology development. The culmination of these techniques in CTA is letting "societal aspects [of innovation] become additional design criteria", rather than allowing the developing technology to become deeply imbedded in technological or social systems, and thereby rendered less malleable, prior to the consideration of social factors.[21] These advances in the Netherlands are related to novel thinking elsewhere, including the attempt of consensus conferences in Denmark and other nations to influence technological design and implementation, the emphasis at the Organization for Economic Cooperation and Development (OECD) on "minimizing mismatches, wrong investments, and possible social conflict", and the focus in both Europe — reflected in the European Union's R&D programs — and the United States — reflected in such work as the Carnegie Commission on Science, Technology, and Governance — on closer interaction between the supply and demand sides of innovation.[22]

The real-time technology assessment described in greater detail below continues on this general trajectory. To preface, however, it differs from the canonical description of CTA (if there is such a thing) in at least three ways: First, although it follows CTA in engaging in socio-technical mapping and dialogue between producers and consumers, it does not engage in experimentation with new technologies because it is embedded in the knowledge creation process itself. It makes use of more reflexive measures such as public opinion polling, focus groups, and scenario development to elicit values and explore alternative potential outcomes. Second, it uses content analysis, social judgment research, and survey research to investigate how knowledge, perceptions, and values are evolving over time, to enhance communication, and to identify emerging problems. Third, it integrates socio-technical mapping and dialogue with retrospective (historical) as well as prospective (scenario) analysis, attempting to situate the innovation of concern in a historical context that will render it more amenable to understanding and, if necessary, to modification.

3. Technology assessment in context

Few would deny the desirability of predicting the variety of consequences of a particular path of technological innovation. Such a goal will never be fully attained, because consequences emerge not from the static attributes of a fully formed technology, but from the complex co-production that simultaneously and continually molds both technology and social context. The essence of this dilemma is vividly illustrated by events surrounding the emergence of nanotechnology as perhaps the next wave of society-transforming innovation.

Nano-scale science and engineering (NSE) is the study, manipulation, and design

[21] Ibid.
[22] Ibid., p. 254.

of materials and technologies at the atomic scale. On one hand, the US federal government is directing more than $400 million in fiscal year 2001 into a NSE initiative, justifying this expenditure by reference to inevitable and sweeping societal benefits.[23] On the other hand, fears of nanotechnology gained credibility with a critique by the influential high-tech entrepreneur Bill Joy of the potentially disastrous consequences of innovation in autonomous, self-replicating technologies that advances in NSE will enable.[24] Promotional rhetoric from the government is as immoderate in its promise of benefit as Joy is in his prognostication of disaster. This tension, not atypical in debates about new technologies, creates a promising opportunity to develop and apply real-time TA at the early stages of what may (or may not) prove to be the next technological revolution.

But it does raise the question of predictability: Need we determine, in advance, whether the federal government's vision of NSE is more accurate than Bill Joy's?

Individual decision makers, and societies at large, are constantly required to act on problems that are on some level unpredictable — from the behavior of the market to the occurrence of natural disasters. Moreover, decision making is an inherently forward-looking activity, in that some degree of expectation of what the future will look like underlies any decision. Thus, preparation for and resilience in the face of an unpredictable future is a core asset of any well-functioning society.[25] For example, American society enjoys something of a consensus that natural disasters are bad things. While individual hurricanes cannot be predicted far in advance, construction codes, land-use planning, and emergency response plans can greatly mitigate their impacts.

Often, the best way to reduce uncertainty about the future of open systems is to make informed but incremental decisions and then see what happens.[26] This approach favors (but does not ensure) consequences that are manageable and error-correction that is both politically and practically feasible. The Federal Reserve Board modulates microeconomic behavior through the macroeconomic tool of slight changes in prime lending rates. Ecosystem management decisions are increasingly conducted as incremental experiments that should always be subject to modification. Such approaches can succeed without explicit maps of the unforeseeable future. But their

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[23] For the budget information, see Intersociety Working Group, Congressional Action on Research and Development in the FY 2001 Budget (Washington, DC: American Association for the Advancement of Science, 2001). For justifications of the federal effort, see Interagency Working Group on Nanoscience, Engineering and Technology, Nanotechnology: Shaping the World Atom by Atom, (Washington, DC: National Science and Technology Council, 1999).

[24] Joy B. "Why the Future Doesn't Need Us." Wired. Available at www.wired.com/wired/archive/8.04/joy—pr.html.

[25] This point emerges from philosophy and political theory, e.g., Dewey J. How We Think (Amherst, NY: Prometheus Books, 1991) and Heilbroner R. The Future As History; The Historic Currents of Our Time and the Direction in Which They Are Taking America (New York: Harper, 1960), as well as public policy, e.g., Sarewitz D, Pielke Jr. R, Byerly Jr. R. eds. Prediction (Washington, DC: Island Press, 2000).

[26] Lindblom CE. The Science of Muddling Through, Public Administration Review, 1950;19:79–88; A. Wildavsky, The New Politics of the Budgetary Process (New York: HarperCollins, 1992).

success is predicated upon significant capabilities in monitoring the system being managed.

From this perspective, the key to successfully grappling with unpredictability is to build a decision process that is continuously reflexive, so that the attributes of and relations between co-evolving components of the system become apparent, and informed incremental response is feasible. Here, the role of social science is to achieve "not prediction with precision, [but] freedom through insight".[27] This perspective is consistent with approaches from several disciplines and goes by such names as "muddling through", "adaptive management", and "sophisticated trial-and-error".[28]

Predictability is thus only necessary if one insists that accurate foreknowledge is required for good decisions about complex systems, and both theory and practice demonstrate the problems of this requirement. But society's capacity to plan despite an uncertain future shows that the alternative to prediction is not inaction or reaction, but incremental action based on synchronous reflection and adjustment.[29] What is necessary, we believe, is to build into the R&D enterprise itself a reflexive capacity that encourages more effective communication among potential stakeholders, elicits more knowledge of evolving stakeholder capabilities, preferences, and values, and allows modulation of innovation paths and outcomes in response to ongoing analysis and discourse. Real-time TA fits this bill.

4. Real-time technology assessment and nanotechnology

In the following presentation, we provide neither a detailed, tactical methodology nor an overarching institutional process, but instead describe a "mid-level methodology" for real-time TA that has been lacking in technology assessment.[30] We use examples from nano-scale science and engineering to illustrate how this methodology might be applied.

Our model of real-time TA comprises four linked components that can lead to an inherently reflexive R&D enterprise. The first component is the development of analogical case studies, as studying past examples of transformational innovations can help to develop frameworks for anticipating future interactions between society and new technologies. The second component is mapping the resources and capabilities of the relevant innovation enterprise to identify key R&D trends, major participants and their roles, and organizational structures and relations. The third component is eliciting and monitoring changing knowledge, perceptions, and attitudes

[27] Brunner RD, Ascher W. Science and Social Responsibility, Policy Sciences, 1992;25:295–331.

[28] For "muddling through", see Lindblom op cit. For "adaptive management", see Lee K, Compass and Gyroscope: Integrating Science and Politics for the Environment (Washington, DC: Island Press, 1993). For "sophisticated trial and error", see Morone JG, Woodhouse EJ. Averting Catastrophe: Strategies for Regulating Risky Technologies (Berkeley: University of California Press, 1986).

[29] Brunner and Ascher, op. cit.

[30] Wood F. Lessons in Technology Assessment: Methodology and Management at OTA, Technological Forecasting & Social Change, 1997;54(2&3):145–162.

among stakeholders, because empirically grounded, research-based strategies can enhance the quality of science communication about the societal implications of innovations. The fourth component is engaging in analytical and participatory assessments of potential societal impacts, conducted because informed societal response to innovation depends on how well various societal actors — ranging from scientists to the general public — are prepared for the evolving impacts of the innovation.

Each of these activities is supported by well-developed method and practice, but they have yet to be conceptually and operationally linked in a coherent approach to technology assessment. Central to our vision is the idea that these activities proceed simultaneously, are mutually supportive, and are fully integrated into the innovation process. This integration means that the R&D process must be reconceptualized to encompass scientists and technologists, social scientists, and a range of potential stakeholders interacting on various levels. The only novelty of this process, however, is rendering explicit and self-aware the currently implicit and unconscious process of co-production.

4.1. *Analogical case studies*[31]

Studying past examples of transformational innovations can help to develop analogies and frameworks for understanding and anticipating societal response to new innovations. In particular, knowledge about *who* has responded to transforming innovation in the past, the *types* of responses that they have used, and the *avenues* selected for pursuing those responses can be applied to understand connections between emerging areas of rapidly advancing science and specific patterns of societal response that may emerge. Moreover, by assessing the variety of strategies and tactics used to manage conflict over, and allocate benefits of, the impacts of new science and technology, case-based approaches can help to conceptualize more effective approaches for the future. Key to the value of this activity is the capacity to identify appropriate analogous cases.

These patterns of societal responses can strongly influence — positively and negatively — the outcomes of research. To help assure beneficial outcomes, public policy for nanotechnology should do more than simply fund R&D — it must also take into account societal responses. This component of real-time TA can support such an accounting. Of course, one cannot make simple extrapolations from retrospective cases to NSE, since each case has its own context and contingent circumstances. But researchers can use the cases to frame hypotheses and create categories of variables to which the study of NSE should attend, guiding and sensitizing the enterprise to issues that otherwise might escape notice.

For example, consider NSE research aimed at developing autonomous, photosynthetic artificial cells. Such technologies could have significant applications in such areas as individualized drug delivery, efficient chemical processing, bioremediation,

[31] We are indebted to Frank Laird of the University of Denver for the development of this section.

and advanced computing.[32] One line of relevant case studies might focus on artificial cells as the latest step in a historical progression of medical implant technologies — prosthetics, organ transplants, xeno-transplants, artificial organs, and so forth. Another might view artificial cells in the context of technological trends toward gradual hybridization of natural and artificial devices. From this perspective, recent experiences with genetically modified organisms — including the differing public responses to medical versus agricultural applications — could help anticipate public concern and responses to different types and applications of artificial cells.

4.2. Research program mapping[33]

While case studies help to situate evolving technologies in their historical context, research program mapping (RPM) monitors and assesses current R&D activities at regional, national, and international levels. The unit of assessment can vary from a single laboratory to an entire field of innovation but, whatever the scale, some effort to map the resources and capabilities of the enterprise is necessary to identify key R&D trends, major participants and their roles, and organizational structures and relations.

The mapping activity is accomplished through standard text-mining and bibliometric approaches, supported by networking and more formal interviewing within the relevant R&D community.[34] These tasks need to be performed longitudinally, thus informing R&D managers, policy makers, and other stakeholders in the NSE enterprise of possible high leverage points (e.g., gaps), emerging opportunities, subtle trends, and major developments. The maps must also be subjected to intensive review by the subjects of the mapping through presentation at relevant conferences and workshops.

RPM profiles R&D efforts by location (regional and international) and type of performer (academic, government, NGO, corporate). This approach can answer such general questions as “who is doing what?” and such specific questions as “which lab in country X is pursuing Y?” In the case of NSE, for example, a simple bibliometric profile conducted in 1995 revealed the participation of a diverse range of researchers.[35] Yet interactions were not universal; there were strong divisions of interest with little cross-fertilization. Continued monitoring of the enterprise should begin to reveal where synergistic collaborations are emerging, and may thus permit early identification of leverage points for focusing TA activities. The overall point is that the capacity to understand “what is going on” from a technical standpoint

[32] We are indebted to Neal Woodbury of Arizona State University for developing the artificial cell discussion.

[33] We are indebted to Alan Porter of Georgia Tech for the development of this section.

[34] For more information, see The Georgia Institute of Technology’s Technology Policy and Assessment Center at http://tpac.gatech.edu and its discussion of technology opportunities analysis.

[35] Porter AL, Cunningham SW. Whither Nanotechnology: A Bibliometric Study, Foresight Update, 1995;21;12–15.

in the embryonic NSE enterprise is a prerequisite for designing effective real-time TA programs.

4.3. Communication and early warning[36]

Communication among researchers, decision makers, the media, and the public significantly determines the complex societal relation with innovation. The communication and early warning (CEW) aspect of real-time TA provides empirically grounded, research-based strategies for enhancing the quality of the communication of scientific, technical, and social developments. Most of the literature on the impact of technology on society has focused on "back end" impacts and, thus, is often not useful as a practical guide to avoiding "front end" mistakes. There is very little work focusing on communication patterns at the very beginning or even anticipating major scientific and technical change and its impacts, to better allow us to understand, prepare for, and avoid conflict, opposition, and backlash — hence, "early warning". The recent controversy over genetically modified organisms offers a cautionary tale about the need for such an approach: few would disagree that stakeholders lacked a satisfactory process to address the issue in a productive manner until it was too late.

CEW activities focus on: (1) content analysis of major media sources for public information about the innovation; (2) social judgment research to assess public concerns about, and aspirations for, the development and application of the innovation; and (3) survey research to identify public reaction to media portrayals of the innovation and to track changes in public attitudes about developments in the innovation. CEW considers not only knowledge and opinion but affect, an underappreciated dimension of risk judgment that is particularly important with respect to technologies that, at least in some groups, can generate fear.[37] CEW activities would allow real-time technology assessors to understand how public attitudes are evolving in the context of both historical trends (as developed in the case study activity) and evolving scientific capabilities (as developed in RPM). CEW also facilitates the identification of public priorities to be addressed in the technology assessment and choice activity (below). But CEW can itself lead to greater knowledge and more effective communication among both researchers and the public, and thus encourage the development of a more open process of technological co-production.

To illustrate how such a process might unfold, consider a new idea emerging from NSE research. Preliminary work on the design of artificial zeolites (aluminosilicate crystals whose nano-scale pores can be designed to particular size and shape

[36] We are indebted to Barry Bozeman and Elke Weber, both of Georgia Tech, for the development of this section.

[37] For ways to measure affect using associative group analysis, see L.B. Szalay and J. Deese, Subjective Meaning and Culture: An Assessment Through Word Associations (Hillsdale, NJ: Lawrence Erlbaum Associates, 1978) and E. Peters and P. Slovic, The Role of Affect and Worldview as Orienting Dispositions in the Perception and Acceptance of Nuclear Power, Journal of Applied Social Psychology, 1986;26:1427–1453. For a review, see Loewenstein GF, Weber EU, Hsee CK, Welch E, Risk as Feelings, Psychological Bulletin, 2001;127:267–286.

specifications) suggests that they may have potential application for remediation of airborne organic pollutants.[38] Nano-scale zeolite crystals with intelligently designed pore size and shapes could capture specific pollutants. These crystals could be disseminated in contaminated air, and they would behave like discrete, free-floating, nano-scale scrubbers to clean up the pollution.

While such an approach responds to public concern about air pollution, one can easily imagine that it would stimulate new concerns and even fears about the consequences of respiration of the crystals and their behavior in the biosphere. CEW activities would elucidate public attitudes about such consequences at an early stage and focus on specific issues that could become "showstoppers" before there is a show to stop. CEW would also identify what groups and sectors have perceived stakes in the outcomes of the research. Such insights could then feed in to the design of participatory activities, described in the next section.

4.4. Technology assessment and choice

Informed societal response to innovation depends on how well various societal actors (from scientists to the general public) are prepared for the evolving impacts of the innovation. Science and technology policy research needs to establish processes that can help society prepare for making actual choices about the progress, direction, and application of — as well as responses to — potentially transforming innovation. The technology assessment and choice (TAC) activities have three main functions: (1) to assess, using such traditional methods as forecasting, foresight, road-mapping, and expert elicitation, the possible societal impacts and outcomes of NSE research; (2) to develop a scenario-based deliberative process for identifying potential impacts of NSE research, and to chart paths, in a participatory fashion, for enhancing desirable impacts and mitigating undesirable ones;[39] and (3) to evaluate the role of real-time TA activities on the evolving NSE research agenda.

The traditional TA function begins by scanning the literature to identify key issues associated with putative impacts of NSE, for example, the short-term implications of initial products of NSE versus the long-term, grand-scale changes[40] wrought by

[38] We are indebted to Nicholas Turro and Ian Gould for developing the artificial zeolite example.

[39] TA practitioners have also adopted — to good effect — participatory methods such as citizens' panels. See Joss S, Durant J (eds), Participation in Science: The Role of Consensus Conferences in Europe (London: The Science Museum, 1995); D.H. Guston, Evaluating the First US Consensus Conference: The Impact of the Citizens' Panel on Telecommunications and the Future of Democracy, Science, Technology, & Human Values, 1999;24(4);451–482; Hörning G. Citizens' Panels as a Form of Deliberative Technology Assessment, Science and Public Policy, 1999;26(5):351–359. For scenario workshops, see Andersen IE, Jaeger B. Scenario Workshops and Consensus Conferences: Towards More Democratic Decision-making, Science and Public Policy, 1999;26(5):331–340; and Sclove RE. The Democratic Politics of Technology: The Missing Half, The Loka Institute (1999), available at http://www.loka.org/idt/intro.htm. For focus groups, see Dürrenberger G, Kastenholz H, Behringer J. Integrated Assessment Focus Groups: Bridging the Gap Between Science and Policy, Science and Public Policy, 1999;26(5):341–349.

[40] Drexler KE. Engines of Creation (New York: Anchor Press, 1986).

the pervasiveness of nanotechnologies, or the implications of NSE for the research enterprise itself versus implications for society more broadly. This traditional TA can combine with research program mapping activities to develop a fuller understanding of what particular NSE laboratories have in hand and in mind. The objective is to establish — through lab visits, review of publications, and interviews — not only a baseline understanding of the current state of research in particular areas of interest (e.g., artificial cells; artificial zeolites), but also a sense of how the researchers perceive the trajectories of their research. The traditional TA function also includes original research into ethical, legal, environmental, social, and other implications of NSE.[41] This work focuses on particular aspects of interest, selected in part on the basis of what is learned about the past in the historical analogies and about public attitudes in the CEW research. This information then contributes to the construction of initial scenarios for the implications of NSE that will be referents for the remainder of the TAC functions.

The second function applies participatory methods to TAC. Many kinds of methods — citizens' panels, consensus conferences, scenario workshops, focus groups, etc. — can be used.[42] But the important aspects are, first, to establish a baseline of public knowledge, values, and concerns and, second, to facilitate interaction between NSE researchers and the public. The third function is to closely monitor the impact of these interactions between researchers and lay-persons on the participants (through a variety of mechanisms, potentially including follow-up interviews, web-based surveys, diaries, etc.) and track any external consequences of these efforts (e.g., actual impacts such as policy decisions; impacts on general thinking such as changes in research and political agendas; and impacts on expert and lay participants' substantive and reflexive knowledge).[43]

An idealized version of these three functions might proceed as follows:

(a) Working with laboratories identified in the RPM activity, real-time TA researchers construct initial scenario for the impacts of nanotechnology, S.
(b) Facilitated interaction between lab researchers and the lay public results in elaboration of scenarios S′ and S″.
(c) Lab researchers discuss scenario S′ and S″ with colleagues, think about different research questions or strategies, make different research or application development choices, or construct different consumer linkages.
(d) Lay participants engage in real learning about the research and its possible applications.
(e) Lab researchers and lay participants describe these activities in interviews, by logging them in web-based survey or in diaries, etc.

[41] Porter AL, Rossini FA, Carpenter SR, Roper AT. A Guidebook for Technology Assessment and Impact Analysis (New York: North-Holland, 1980) and Porter AL, Roper AT, Mason TW, Rossini FA, Banks J. Forecasting and Management of Technology (New York: Wiley, 1991).

[42] See discussions in Vig and Paschen, op. cit.

[43] For a schematic protocol for assessing the impact of participatory technology assessments, see Guston DH. Evaluating the First US Consensus Conference, op cit.

(f) Real-time TA project documents emergence of S′ or S″, in contrast to S, as an outcome.

A fundamental and testable hypothesis emerges: that participatory, deliberative processes will stimulate efforts to enhance desirable impacts and mitigate undesirable ones through decisions made by NSE researchers about research priorities and directions. Moreover, broader policy issues may emerge, and the real-time TA researchers could take such an opportunity to develop policy options for wider dialogue and action through, for example, additional outputs including op-eds or other general writing by collaborating with participant lab researchers and lay participants.

The appropriateness of such an approach to the examples of NSE research mentioned above — artificial cells, and artificial enzymes — is obvious. For example, the release of autonomous artificial cells into the environment and the health implications of respirable artificial zeolites could well engender public concern. Early articulation of such concern, before innovation trajectories are wired into the marketplace, could inform research strategies and goals, and thus lead to greater concordance between public aspirations and NSE innovation activities.

5. Implementing real-time technology assessment

We realize that the foregoing description of a real-time TA protocol is highly stylized. Our goal has been to provide not a recipe but a mid-level framework showing, in principle, how a range of well-established social science activities could be linked to create a coherent and societally beneficial approach to technology assessment. In practice, several obstacles to implementing such an approach can be expected.

5.1. Problems of scale

We have used emerging NSE research as a context for presenting our real-time TA model but, even at this early stage, NSE activities are broadly disseminated through the R&D enterprise. Indeed, all nations with significant R&D capabilities are now engaged in NSE activities. The variety of potential applications for NSE, including targeted drug delivery, gene therapy, energy storage, ultra-strong materials, single-molecule sensors, and terabyte computer memory, is huge and growing.[44] To the extent that an NSE enterprise can be said to exist, it is already too large and diverse to be the subject of a single TA effort.

The key, therefore, will be to select pilot projects that are likely to be successful (aided by the RPM activity described above). Since success means not only the implementation of the real-time TA itself, but also the enhanced capacity of the

[44] Interagency Working Group on Nano Science, Engineering, and Technology, Nanostructured Science and Technology: A Worldwide Study (Washington, DC: National Science and Technology Council, 1998).

innovation process to deliver public benefit, we would expect that the desire (in both the public and private sector) to implement real-time TA protocols should propagate on the heels of well-publicized successes. Several decades ago, the idea that energy efficiency and pollution prevention measures should be integral to private sector endeavors might have seemed equally quixotic. We imagine that a similar time-frame would be necessary to gain broad acceptance for the real-time TA process.

5.2. Problems of participation

Given the embryonic state of NSE, how can stakeholders be identified when the stakes are not yet elucidated and allocated? What would motivate the public to participate in TA activities? One lesson of nuclear power and genetically modified organisms seems to be that public concern usually mobilizes after a technology reaches the marketplace — long after, in some cases (e.g., the internal combustion engine). While the value of our model lies in its "real-time" creation of a reflexive capability at earlier stages in the R&D process, this same characteristic may render these activities too abstract to elicit the desired involvement of non-expert communities.

One approach to overcoming this obstacle is to choose pilot projects that raise issues similar to those found in existing public controversies about the use of technology. Thus, latent but potentially motivated stakeholder groups may already exist. Artificial cells and zeolites could fall into such a category. However, where NSE frontiers are advancing rapidly, it may still be desirable to develop a TA effort even in the absence of organized societal stakeholders. In such cases, effective marketing (perhaps augmented by some financial compensation) may be necessary, as in other participatory processes such as blood donation, clinical trials, and psychology experiments.[45]

5.3. Problems of organization

Central to our model is close collaboration among natural scientists, social scientists, and members of the public. Obstacles to interdisciplinary research are legion and well-documented,[46] and in this case such obstacles may be exacerbated by the differing goals of the social scientists who are trying to implement the TA process and the NSE researchers. All the same, our own preliminary experience with NSE researchers at Columbia University and Arizona State University has shown a receptiveness to collaboration on TA activities, rooted in a desire to contribute to societally beneficial outcomes. Moreover, the idea of natural scientists and engineers, social scientists, and stakeholders and the lay public working together is not itself novel or far-fetched. There are many instances of anthropologists and sociologists conducting

[45] Dickert N, Grady C. What's the Price of a Research Subject? Approaches to Payment for Research Participation, New England Journal of Medicine, 1999;341:198–203.

[46] Klein JT, Interdisciplinarity: History, Theory, and Practice (Detroit: Wayne State University Press, 1991).

participant-observation in natural science and engineering laboratories. In the process of technology transfer from university and government laboratories to the private sector, social scientists and marketing, business, and legal professionals collaborate with natural scientists and engineers to assess the potential of an innovation for patenting, licensing, and marketing. Agricultural and technology extension programs are successful examples of collaboration between such different types of experts. And in consensus conferences conducted in many countries, lay-citizens have demonstrated their competence to engage questions with significant technical content and help scientists and policy makers frame and analyze such issues.[47]

5.4. Supporting real-time TA

Finally, the question of how these activities will be supported looms large. To date, no US R&D programs of which we are aware include an integrated technology assessment component of the type presented here.[48] However, ten years ago there were no ELSI programs attached to federal science initiatives, and today they are well accepted. In one sense, real-time TA, where the social science activities are fully integrated with the core natural science agenda, is a small evolutionary step from the current ELSI model. In another, however, such a step requires not only that research administrators recognize the reality of technological co-production, but that they value making it an explicit part of the research process. Again, this step is most likely to be taken if framed as an experiment or pilot project. The most likely structure to accommodate such an innovation is the same kind of "overhead" that funds ELSI research, with a small percentage of the total program budget allocated for real-time TA.

6. Conclusion

The most important challenge that science and technology policy now faces is neither one of funding increments nor of the large-scale structure of the enterprise: R&D spending has wide bipartisan support among both elites and the public and, although one may fret about the distribution of R&D tasks among performing sectors

[47] Primary examples of participant-observation include, of biomedical research Latour B, Woolgar S. Laboratory Life (Beverly Hills, CA: Sage Publications, 1979) and of physics, Traweek S. Beamtimes and Lifetimes (Cambridge: Harvard University Press, 1988). For collaboration in technology transfer, see Guston, Stabilizing the Boundary between US Politics and Science, op. cit. For agricultural extension, see Cash, op cit., and for technology extension, see Kolodny H, Stymne B, Shami R, Figuera JR, Lillrank P. Design and Policy Choices for Technology Extension Organizations, Research Policy, 2001;30;201–225. For consensus conferences, see the references in n. 38 supra.

[48] Although the Economic and Social Research Council of the United Kingdom has initiated a new, five-year, million-pound program on science in society that could support similar collaboration between social and natural scientists.

and the blurring of boundaries among them,[49] the collaboration of government, the private sector, and institutions of higher education is a satisfactory and even a robust infrastructure.

Likewise, the overarching goal of using research and research-based innovation to improve the human condition is well-established, although it is not always well-articulated.[50] Rather, science and technology policy must learn to shepherd the success of the R&D enterprise under this goal. It must develop new approaches, within the existing infrastructure, that help assure that research and research-based innovation most effectively contribute to an improved quality of life for the greatest number of people. Real-time technology assessment is one modest but critical element — modest because its novelty derives from the assemblage of previously tested components, and critical because it is designed to solve extant problems faced by both researchers and society generally.

Real-time TA's analogical case studies hold promise for encouraging contextually sensitive innovation. Its research program mapping improves opportunities for strategically oriented innovation. Its communication and early warning component helps assure awareness about innovation among researchers and the public, and its technology assessment and choice component provides a mechanism for such awareness to be reflexively incorporated into innovation. These activities of real-time TA are not predicated on the illusion that research can be planned or its impacts foreseen. Indeed, real-time TA is necessary precisely because planning and perfect foresight are illusory. But proceeding without the capacity embodied by real-time TA is a similarly grand deception.

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[49] For example, see Mowery DC, Nelson RR, Sampat BN, Ziedonis AA. The Growth of Patenting and Licensing by US Universities: An Assessment of the Effects of the Bayh-Dole Act of 1980, Research Policy, 2001;30:99–119.

[50] This articulation is the essential purpose of the recent language of "Jeffersonian science". See Branscomb L, Holton G, Sonnert G. Science for Society: Cutting-Edge Basic Research in the Service of Public Objectives, A report on the November 2000 Conference on Basic Research in the Service of Public Objectives (Cambridge: Harvard University, 2001).