On the Future of Technological Forecasting

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ABSTRACT

Technological forecasting is now poised to respond to the emerging needs of private and public sector organizations in the highly competitive global environment. The history of the subject and its variant forms, including impact assessment, national foresight studies, roadmapping, and competitive technological intelligence, shows how it has responded to changing institutional motivations. Renewed focus on innovation, attention to science-based opportunities, and broad social and political factors will bring renewed attention to technological forecasting in industry, government, and academia. Promising new tools are anticipated, borrowing variously from fields such as political science, computer science, scientometrics, innovation management, and complexity science. © 2001 Elsevier Science Inc.

Introduction

Technological forecasting—it's purpose, methods, terminology, and uses—will be shaped in the future, as in the past, by the needs of corporations and government agencies. These have a continual pressing need to anticipate and cope with the direction and rate of technological change. The future of technological forecasting will also depend on the views of the public and their elected representatives about technological progress, economic competition, and the government's role in technological development.

In the context of this article, "technological forecasting" (TF) includes several new forms—for example, national foresight studies, roadmapping, and competitive technological intelligence—that have evolved to meet the changing demands of user institutions. It also encompasses technology assessment (TA) or social impact analysis, which emphasizes the downstream effects of technology's invention, innovation, and evolution.

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1 The term "technological forecasting" is used in this article to apply to all purposeful and systematic attempts to anticipate and understand the potential direction, rate, characteristics, and effects of technological change, especially invention, innovation, adoption, and use. No distinction is intended between "technological forecasting," "technology forecasting," or "technology foresight," except as specifically described in the text.

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In early 1999, a number of technology futurists scattered around the globe began to exchange ideas about the future of TF and TA, through e-mail and face-to-face meetings. Many such exchanges over the subsequent 18 months have resulted in this cooperative draft by seven authors, of a normative forecast setting out how we hope to see TF/TA develop over the coming 20 years. This is a work in progress, incorporating multiple perspectives on where TF and TA have come from, and where they should be heading. Through this still mutable draft and by presentations in various professional venues we hope to provoke broader discussions and galvanize support for the development of more effective, widely recognized, and better utilized TF and TA.

It is the theme of this article that successive steps or phases in the development of TF have been and will be driven by institutional needs and motivations and by broad social changes over the next decades. We will first briefly review the evolution of TF/TA, then turn to its social, political, business, and institutional drivers. Following this discussion, we will consider the new directions, that is, the emerging forms and tools.

The Development of TF/TA

Perhaps the first official account of a systematic outlook on the future of science and technology occurred in 1935 through the New Deal’s National Resource Commission, which tasked a committee to look into the future of 13 major inventions. The resulting report sought to predict the economic and social impact of these emerging technologies [1]. (Note that at this early point TF included what would later become TA.) The report was widely publicized in the business press and one can infer that the concern at that time was primarily about the effects of technological change [2].

After World War II Vannevar Bush presented the U.S. scientific enterprise with a blueprint for post-war science policy by depicting a model of innovation in which technology flows from basic science to product development and commercialization [3]. The depiction of a linear and causal relationship between investments in basic science and technological innovation held in abeyance concern over the direction of technological change, while concentrating mostly on the rate of technological change, particularly following the Sputnik shock. This emphasis also catered to the needs of the U.S. defense establishment, where directional uncertainties were minimized given the Cold War focus on successive generations of weapons systems. As a consequence, first generation R&D management strategy in both industry and government had strong input; its emphasis was on funding research, setting up labs, and establishing research teams [4].

Cold War competition brought forth the need to cope with dramatic developments in technology such as guided missiles, nuclear weapons, and computing. Systems analysis became an important tool in designing such complex systems. The military–industrial complex needed ways of anticipating levels of performance in weapons and components, and ways to set feasible performance goals.

By 1949, largely under the aegis of the U.S. government, the development of TF as a systematic means of exploring the future of technology was under way. Grounded in systems analysis, TF helped military strategists deal with the complexity and long lead times necessary to develop modern armaments and anticipate probable countermeasures. During the next decade, the focus was on forecasting the rate of technological change. Quantitative exploratory methods, working from the past to the future, included trend extrapolation, leading indicators, and growth models. But normative forecasting, starting with perceived future needs, played a role as well. The mix also fostered more qualitative approaches such as relevance trees [5], mission flow analysis, scenario writing,
and Delphi [6]. The first textbooks on TF described not only these tools but placed them into the planning and decision making context as well [7, 8].

The introduction of formalized helped TF to build constituencies in industry, government, and academia [6-13]. By the late 1960s journals, textbooks, and conferences on TF extended far beyond the U.S. defense establishment. However, this expansion occurred at a time when science and technology policy making was in disarray because of newly developing environmental and social consciousness on the one hand and pressures on corporations for early payoff for investment on the other [14].

Disillusionment with systems analysis spread in the 1970s with the failure of its ability to deal with ill-structured systems (for example, Vietnam, urban systems). The 1973 oil-shock revealed some of the effects of geopolitical instabilities on the prediction of technology futures. Hence support for TF within the policymaking arena faltered during the late 1970s and 80s as it was realized that the uncertainties of technology development defied clear-cut “systems analysis” solutions. There was also growing realization that long accepted scientific paradigm procedures such as validation and replication could not be applied to confirm the forecasting tools beyond the near term. These are concerns that will be illuminated in the discussions of multiple perspectives and complexity science in the section on Emerging Tools for TF/TA.

Support for centralized corporate R&D operation also weakened with the end of uncontested dominance of U.S. firms in global markets and a resulting decline in profitability for many firms. Technology-intensive firms began to shift towards decentralized R&D management, a second generation of R&D management strategies. TF was reduced in practice to a set of tools and methods; forecasts produced between 1975 and the early 1990s were relatively few, generally poorly defined, and executed without much attention to formal assumptions, time horizons, or limitations [15].

The Shifting Setting for TF/TA

Our society is now completely reliant on technology—to drive the economy, to maintain and improve standards of living, and to protect Earth against the pressures of population and urban living. Nations are irretrievably enmeshed in a global economy fueled by innovation and competition. Therefore, technology is an increasingly important and challenging target for analyses to aid decision makers.

From its beginnings over a half-century ago, the development of TF has responded to ever-changing organizational needs, in both the private and public sectors. From the late 1940s through the mid-1970s both quantitative and qualitative methods were developed, refined, and used; in many cases they were independently developed at different times and given different names in several organizations. Then, for nearly two decades, a lag in responding to changing institutional and social needs resulted in a seeming decline in the acceptance and usefulness of traditional TF. But, in fact, during this period a number of closely related variants, or supplementary ways, of looking to the future of technology, began to evolve: technology assessment, national technological foresight, roadmapping, and competitive technological intelligence.

At present, the challenges posed by rapid technological change, organizational complexity, and social forces demand effective information on emerging technologies. The decade of the 1990s has, therefore, initiated an upsurge in all forms of TF, using both old and new techniques and with much commonality of purpose.

The several authors of this article, from their multiple perspectives, see the following points as key to the future of TF for the coming decades:
1. The applications of new technology, rather than invention per se, is the payoff for TF, and this requires understanding of many organizational, market, and social factors. The change in the clientele of TF following the Cold War, therefore, recasts its context significantly. Economic, not military or political, competition is now the primary motive to undertake TF, and public policy makers are acutely aware of the importance of market competitiveness in international leadership and national security.

2. Technological developments are increasingly drawn directly from scientific research. This implies a need for tools to address less than orderly change processes. “Science forecasting” is called for to support and serve technology foresight.

3. Social and political conditions appear to favor the reemergence of both TF and TA. New, socially transforming technologies, such as genetic engineering, are widely perceived as risky or ethically questionable. The inequitable distribution of the benefits and costs of technology have become highly visible in the form of dot.com millionaires and corporate downsizing. Similar perceptions, in the 1960s, gave birth to environmentalism and TA, and their resurgence today may lead to new demands for better anticipation and management of technology.

4. The TF toolkit is expanding—old tools retain value but are being supplemented by powerful new tools that exploit electronic information resources and deal with complex systems and apparently chaotic behavior.

5. Platforms for TF are changing and becoming much more integrated with company functions and policy setting. There is growing recognition that the organizational processes of deriving and implementing technology roadmaps, competitive technological intelligence, and national foresight should be valued more than the accuracy of the forecasts.

6. Both the customers for and the practitioners of TF and TA are becoming more diverse; and customers must increasingly be urged to participate in the analyses.

Social and Political Drivers of TF/TA

For both societal and institutional reasons, the time is ripe for resurgence of interest in TF/TA. In the first two decades of TF, attention focused chiefly on extrapolation of trends in the evolution of technologies. The TF community did not completely ignore social considerations, and Harold Linstone, who founded the journal Technological Forecasting in 1969, after just 1 year of publication changed the name of his journal to Technological Forecasting and Social Change. Nevertheless, the impetus for systematic analysis of the potential consequences of emerging technologies, that is, technology assessment, came not from the TF community, but from the U.S. Congress, where a proposal to establish an Office of Technology Assessment was introduced in the late 1960s, and passed in 1969. OTA began operating in 1973.

Throughout the 1960s there had been growing disquiet over the health, social and environmental impacts of new or expanding technologies. This disquiet challenged a major paradigm in American culture, faith in technology as the vehicle of Progress. A series of disclosures about industrial pollution, disruption of communities by urban redevelopment and highway construction, the possible sonic shock wave effects of the supersonic transport, the thalidomide disaster, and other undesirable outcomes of technology captured public attention. Rachel Carson’s The Silent Spring and the first Earth Day galvanized concern. The challenge gave rise to two great and closely related movements, environmentalism and TA.
While TF responds to the institutional needs of both public and private sector institutions, TA—because of its analytical scope and the broad institutional responsibilities that are implied—is most appropriately used in the public sector. It fits less well in narrower purpose and highly competitive corporations that do not have comprehensive social responsibilities. The institutional champions of TA and environmental impact analysis in the 1960s and 1970s were federal agencies forced by critics to defend their urban development and highway building projects against charges of community disruption and environmental degradation. In this context, increased levels of technological performance were not viewed as either inevitable or desirable per se. In subsequent decades, as governments tried to respond to energy crises and later to world market conditions, the balance shifted from anticipation of problems toward identification of opportunities for technological innovation.

Logically a good technology assessment should build on well-done forecasting, and sound technology forecasting should include assessment of the downstream effects of changes in technology [16]. The two forms of analysis use many of the same methods—trend extrapolation, expert opinion, modeling, scenarios, and so on [17].

Environmentalism was to a large extent a defensive response: protect nature and natural resources against the depredations of people and technology. The National Environmental Policy Act of 1969 forced government agencies to look systematically at the possible ecological and social consequences of some applications of engineering technology. Public participation techniques were introduced to help with this foresight, and later became part of the TF repertoire of methods. TA went further; it was an attempt to provide a bridge between traditional political institutions and the dynamic, driving world of technological advancement and industrial expansion. TA, it was suggested, might provide an “early warning system” through which decision makers could become more alert to the long-range implications of technological development and related governmental decisions, projects, and programs.

What encouraged widespread concern about the future of technology was that growing numbers of people felt a deepening skepticism of, or at least reservations about:

1. technological progress—there was growing recognition that technology could have unplanned, unsought, and unanticipated consequences,
2. unconstrained capitalism and free markets—there was renewed recognition that both the much touted benefits of technology and its social costs were very unevenly distributed, and
3. scientific and industrial integrity and responsibility—there was a growing suspicion that critical actions and choices made by the technocratic elite, invisible to ordinary people and their political representatives, were determining the nature and quality of everyday life.

Three decades later, these cultural themes are again gathering strength. A family of new and socially transforming technologies is suddenly highly visible. Most people poorly understand computer networks, genetically engineered foods, human genetic manipulation, brain science, and advanced composite materials, no less the coming nanotechnology. Therefore they are widely perceived as risky to people or the environment, and/or threatening to traditional or religious values. The unequal distribution of technology’s benefits and costs is also again highly visible. While the broad economic benefits of the recent “transforming technology,” computers, and telecommunications are generally recognized, the publicity given the powerful software companies and the young Internet multimillionaires, contrasted with the declining real income of many
working families, arouses resentment. Pharmaceutical companies trumpet their newest miracles, but many people cannot afford the drugs they need. Global trade and free markets are hailed as economic bonanzas, but many people still fear the loss of jobs, or at least of traditional job security in the midst of general prosperity. At the same time, Americans and others are much aware that economic prosperity depends entirely on continuing technological innovation and leadership. The resulting ambivalence about technological change, scientific advances, free markets, and industrial responsibility perhaps argues for a resurgence in demand for TF/TA.

The structure of the U.S. Congressional Office of Technology Assessment (OTA) reflected still another broad American theme, tension between the legislative and executive branches of government. Specifically, in this period of large scale, government-funded construction projects, Congress was increasingly suspicious of the information provided by executive branch agencies in their justification, and therefore, created for itself a dedicated source of technological information and advice. Again in 2000, Congress finds itself beset by confusing and conflicting information and advice from trade associations, interest groups, corporate lobbyists, study houses, experts, and self-styled ethicists, many of whom are ideologically driven, and some of whom are misinformed, misled, or just ignorant. Whether the same or different political parties control the Congress and the White House, tension often rises between those branches. In the near future, Congress may again acknowledge the need for its own source of analysis.

The TF/TA community of the 1970s naturally assumed that OTA would be the flagship of the movement, building on and carrying forward the experience built up since World War II. But from the beginning, OTA directors and program managers shunned that association, privately insisting that OTA's business was not technology assessment but “general policy analysis.” At the end, this contributed to OTA’s downfall. Although its work was widely admired, OTA had not cultivated a strong academic constituency ready to spring wholeheartedly to its defense in the time of crisis [18]. Other technology TF/TA programs and associations had been weakened by OTA's nonsupport. Funding for OTA ceased in 1995.

The strengths and accomplishments of OTA have been widely touted, and need not be repeated here. But it is important to note that any attempt to recreate in the United States an institutionalized capability for policy-oriented TF/TA need not, and probably should not, use the late OTA as its institutional model. Alternative structures, locations, processes, and methodological approaches are suggested by the technology assessment institutions that have been created in several European countries and still other models could be attempted on the basis of lessons learned from OTA’s downfall [19]. The precipitating events that could presage overwhelming pressure for better impact assessment and a new institutionalization of technology forecasting/technology assessment in the United States, might be:

1. some large disasters, such as regional crop failures or health threats blamed on bioengineered seed, financial crises resulting from network outages, immune system collapses caused by pharmaceutical mistakes;
2. growing resistance to perceived loss of privacy, widespread business failures, or rampant fraud and money laundering associated with e-commerce or digital money,

2 The International Society for Technology Assessment disbanded in the late 1970s; the International Association for Impact Assessment, founded in 1981, renewed professional society interest in Technology Assessment, but combined with other forms of generic “impact assessment” [see http://www.iaia.org].
3. injuries or deaths caused by new man-made or reengineered materials in buildings, infrastructures, or vehicles,
4. evidence that TF/TA institutions had anticipated or prevented such disastrous consequences in this or other countries, or that early public awareness in this country might have prevented them.

Outside of the United States, technology policy issues—energy, communications, transportation, agriculture, urban development, and environmental degradation—bedeviled governments around the world in the 1980s. Global economic competition also focused their attention on the necessity of invention and innovation. Respect for the work of the United States’ Congressional OTA was still another factor moving a number of governments and international organizations to institutionalize a capability for TF/TA. These organizations differ in structure, mission statements, authority, and funding arrangements, but the efforts they undertake are very similar [19]. Most carry out a mix of TF/TA, and for most, their recent studies and reports have emphasized bioengineering, information technologies, and environmental concerns. For example:

1. France’s Office Parlementaire d’Évaluer des Choix Scientifiques et Technologiques (Parliamentary Office for Assessment of Scientific and Technological Choices) (1983) is a small, specialized staff to the Parliamentary leadership.
2. Britain’s Parliamentary Office of Science and Technology (POST, 1987) has a tiny staff—five analysts—but draws on experts in academia and industry to help generate its reports.
3. Germany’s Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB), serving the Bundestag, contracts out much of the research to an Institute for Technology Assessment and Systems Analysis within the highly respected Fraunhofer Institutes.
4. The Netherlands’ Rathenau Institute is within the Academy of Science but reports to the Minister of Education and Sciences. Denmark’s Teknolog-Rådet (Board of Trade) is a “permanent independent institution” charged with both advising the parliament and encouraging public discussion of technological impacts. Each of these institutions has pioneered use of public participation in determining public policy directions.

An Institute for Technology Assessment within the Austrian Academy of Science receives funding from the Academy (25%), the Ministry of Science and Transport (25%), and research projects funded by clients, usually other government agencies (50%).

The European Parliament has a Scientific and Technological Options Programme to provide information to members on technical issues and impacts, and also a Technology Assessment Network that coordinates TA efforts in member countries. There is also a European Union Institute for Prospective Technological Studies.

TF is an aspect of the work of these organizations, but more systematic TF is carried out by or for the ministries concerned with science, technology, or industry. Delphi surveys and expert panels are the techniques generally used. The Japanese government has conducted six TF Delphi’s since the 1970s. Great Britain and Germany have also conducted national Delphi’s, and in Austria, in 1997, the Ministry of Science commissioned a Delphi Survey to provide the basis for a National System of Innovation. There are other national forecasting programs in France and Australia [20].

The term technology foresight or national technology foresight has increasingly been used to signal the role national governments are playing in identifying socially desirable technologies.
Business and Institutional Drivers of Progress in TF

The future of TF will also be shaped by a new emphasis on innovation and by the growing importance of science-intensive industries. The Cold War has been replaced by escalating economic conflict, and a nation’s competitiveness depends on the capacity of its industries to innovate [21]. Innovation has two components—innovation and market exploitation. It is, in effect, “the result of the confluence of a new technical idea with a market opportunity” [22].

In traditional TF, the main thrust was on the “prediction of the future characteristics of useful machines, procedures and techniques” [23], and forecasts were chiefly measured by whether or not they came true. The inherent problems that are associated with prediction amid conditions of uncertainty are often cited as root causes of the decline in TF popularity; but a more important factor may be that what users wanted or expected from a technology forecast changed. Both government and industry are now more interested in the market exploitation component of innovation than in the invention component. Technology forecasts that focus only on the technical side present only part of the answer.

Also, as the central role of technological innovation in competitiveness becomes more prominent, the need for its formal and structured planning and management increases. Companies rise and fall on the ability of their managers to respond to market dynamics. TF has thus revived in the 1990s in new forms. The primary criterion of success now is whether the forecast supports decision making, and thus may contribute to successful innovation. Assessing technology-related threats and opportunities, and their effect on the organization’s bottom line has become a major goal of technology forecasting.

Traditional methodologies such as monitoring and scanning, trend extrapolation, expert opinion, simulation, and scenario construction have not been discarded, but are incorporated into larger and richer frameworks, integrated with competitive technological intelligence techniques [24], technology and innovation audits, and market analyses [25]. Client participation has become important; Bonickson at UCLA and The Futures Group pioneered the use of computer-assisted participation. Forecasts are increasingly evaluated against the backdrop of global political, environmental, economic, social, and related trends. British national foresight studies use groups of business participants to generate lists of needed technologies that could potentially contribute both to the economy and to the quality of life in Britain.

The spectrum of users of TF may, therefore, change in the next 20 years as their needs change. For example, we may see a shift from national R&D programs to the emergence of national programs of innovation. National technology foresight exercises result in a large overlap in the technologies identified because technology is globally pervasive. Much of the value of a national foresight exercise is, however, derived from the market related aspects—how the particular country will benefit from a given technology or innovation. Technology foresight must address how to appropriate benefits from technology in the quest for competitiveness, and the extent to which innovations can lead to the creation and destruction of new industries or to new market leaders within a particular industry [26, 27].

The same innovation focus is evident in the private sector. Companies now realize that technology decisions are just as much business decisions as are financial, marketing, or other strategic decisions. Hence, technology forecasts must link the technological future to corporate well-being. TF will be elevated to a more strategic level, calling for technical literacy at a higher level of management, and even at the board level [28].
Science-intensive industries are another emerging institutional force. Many great industries have evolved from scientific discovery; examples are aeronautics, electronics, and telecommunications. Nevertheless, many people argue that a growing percentage of innovations today appear to arise more immediately and directly from scientific research. Science-intensive industries, as identified by the large proportion of patents held within the industry that cite peer-reviewed scientific papers, are increasing [29]. In 1960, fewer than 10% of patents in any industry cited scientific papers. Now 90% of the patents in biology-based industries, such as pharmaceuticals, cite scientific papers, as do 50% of patents in chemical industries and 35% of patents in physics-based industries such as computers and telecommunications. Almost every manufacturing industry is becoming more science intensive, and new forms of TF are likely to emerge in order to address their needs.

Some forms of TF have not given great emphasis to the identification of science-intensive technological opportunities, and thus may prove inadequate as more technology becomes science intensive. Technology development tends to be goal directed, and tools such as trend extrapolation, which imply goal-directed behavior, are appropriate. In scientific exploration, goals are often indeterminate. In science, progress is chaotic or at best highly complex, because science is based on self-organizing principles. Self-organizing phenomena often result in sudden and significant changes in direction in a short period of time. The rate and direction of change are not consistent over time. Therefore, different forecasting methods may be needed.

As an analogy, forecasting science-based technology may be like forecasting today’s weather. Very long-range climate trends, alternative scenarios, or panels of experts are less effective than getting a rich contextual picture of the weather (perhaps from the weather channel) and looking at very recent trends such as direction and speed of weather fronts. Experts develop formal models of the weather, and then track the performance of these models to determine which ones to believe. TF may have to turn to computer modeling, especially the modeling of complex self-organizing processes, to forecast science-intensive technological development. Experts will need to develop formal models of the relationship between science and technology and track the performance of these models over time. It may be quite a while before we can use the tools and techniques developed for other phenomena to forecast the timing and location of a scientific breakthrough that can, in turn, be exploited by industry.

**Emerging Forms of TF/TA**

National technology foresight has already been noted. Another growing activity is technology roadmapping, which projects major technological elements of product design and manufacturing together with strategies for reaching desirable milestones efficiently. Roadmaps typically run several technology or product generations (e.g., 2 to 10 years) ahead. In its broadest context, a science and technology roadmap provides a consensus view or vision of the future science and technology landscape available to decision makers [30]. Thus, the predictive element emphasized in early TF is supplemented with a normative element, that is, however, narrower, more targeted, and more directly actionable than is the normative element implicit in TA.

In the past, the institutional champions for roadmapping were mainly military-industrial organizations; more recently, they have been other large corporations and industry associations. But roadmaps are often meant to create a plan of action to capture or recapture markets for technologies considered critical for national security. For private sector organizations, the term “roadmapping” to cover a badly needed corporate
activity has special benefits: it avoids older terms such as “strategic planning” and “forecasting” that acquired a bad odor either from earlier failures or by association with overly centralized R&D management. Industry associations had been more or less forbidden from undertaking “strategic planning,” but found they could sponsor roadmapping exercises in which their corporate members were eager to participate. Corporations, in turn, came to see company-wide roadmapping as a nonpejorative way to assist or redirect faltering R&D projects.

TF usually focuses on specific technologies, but sometimes the scope is more encompassing. A firm might roadmap a set of related technologies and products; an industry association might roadmap the gamut of emerging technologies potentially affecting its sector; or a nation could roadmap technologies across its economic base. For example, a U.S. semiconductor industry association roadmap, regularly updated to support industry planning, had as its early objective regaining global market share in semiconductors. If semiconductor technologies were addressed in a national foresight study, the scope might also include the needs and capabilities of the relevant sciences at the input end, and the possible societal costs and benefits at the outcome end.

Methodologically, both national foresight studies and roadmapping usually bring together people representing different expertise and interests, and use instruments and procedures that allow participants to simultaneously adopt a micro view of their own disciplines and a systems view of overriding or shared objectives. At the macro level, they may rely on participatory processes such as Delphi [10] to draw inferences. These “new” fields have close ancestors in earlier TF work. Aerospace companies did foresight-type studies beginning in the 1950s (i.e., Project MIRAGE 70, 75, and 85 [31, 32]). In the 1960s, Honeywell developed PATTERN (Planning Assistance through Technical Evaluation of Relevance Numbers [5]) and A. D. Little, Inc. did work similar to science roadmapping [33].

Competitive technological intelligence is “the process of identifying technology-based threats and opportunities” [24]. This phrase emerged strongly in the 1990s; and the institutional champions were large corporations in science-intensive technologies, especially pharmaceutical, chemical, and electronics firms (although firms not known for developing their own technology also perform such work). Many of these forms of forecasting use similar tools to accomplish similar ends. But there is a general tendency in government to use phrases that separate thought from action, such as “assessment” and “foresight,” while in industry there is a tendency to use phrases that link thought and action, such as “roadmapping” and “competitive technological intelligence.” Perhaps this reflects the inherent separation of powers in government and the confluence of power within a firm.

There are crossnational differences as well, propelled by differences of societal expectations from markets and governments. Industrial roadmapping, a largely private sector led initiative, originated and became prevalent in the United States, while foresight, a government sponsored activity, became the preferred alternative in Europe. These forms of forecasting—national technology foresight, roadmapping, and competitive technological intelligence—came into prominence at different times, and with relatively little effort to clarify their similarities and differences. For example, some TF textbooks published as late as 1993 do not mention roadmapping or national foresight.

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3 Large-scale multiclient TF was one of three major forecasting services of ADL. For instance, in 1962, ADL carried out a $300,000 project on microminiaturization in electronics for 12 large U.S. companies when integrated circuits were imminent.
studies, although both terms were in use at that time [23]. On the other hand, a 1989 textbook on foresight emphasized differences by saying “research foresight cannot be equated with forecasting, not even with long-term research planning” [34]. Japan’s National Delphi Study is still called “technological forecasting,” but its slightly modified version was introduced in Germany as “foresight” [35, 36].

Do these different terms reflect a fundamental change in a firm’s, industry’s, or government’s approach toward looking into the future? One way to answer this is to take an evolutionary view. The definition of TF as the anticipation of technological change [37] allows us to look at, as independent variables, not only the evolution of understanding of technological change, but also its management in both government and industry.

Emerging Tools for TF/TA

The evolving drivers and challenges are prompting technology analysts to consider new approaches to forecasting and assessment. As of 2000, seeds have begun to sprout that promise a new generation of tools. Some of these are modifications of older techniques, and some are being adapted from related disciplines such as political science, innovation management, scientometrics, and computer science.

SCENARIO MANAGEMENT

This is an example of elaboration and improvement of a basic TF/TA tool [38]. Gausemeier and associates have developed a computerized scenario management process that is particularly well adapted to entrepreneurial business decisions [39]. It allows the inclusion of company-specific organizational perspectives in developing strategies. Starting with an assessment of the decision field (e.g., market share, distribution, profit, functionality, service), scenario fields are developed. These encompass 60 to 150 influence factors, drawn from areas such as the industry competitors, customers, suppliers, and the global environment. External and internal scenarios can be created. An influence matrix helps to select the key factors. Their possible developments are projected into the future and, using cluster analysis; these are then grouped into a few contradiction-free scenarios. For example, for an ATM manufacturer the key factors might include buying habits, home shopping, cashless money transfer, and communication costs. The consequences of the resulting scenarios for the decision field are determined. Alternative strategies can then be evaluated in terms of a single scenario focus or in terms of robustness based on multiple scenarios.

TRIZ

During the 1950s and 1960s, one approach to TF was developed in the Soviet Union by G. Altshuller. He used the analysis of hundreds of thousands of patents to deduce patterns of technological innovation and to postulate laws of technological system evolution. The work, known by the acronym TRIZ, was published only in Russian, and for decades was little known in the West. Now further development of TRIZ is under way, with emphasis on directed technology evolution. This formalized procedure allows for the proactive identification of a strategic objective and development of tactical plans for achieving it. Clarke illustrates the TRIZ approach with the case of endoscopic surgical instrumentation [40]. First, he traced the evolution of existing systems for wound closure—sutures and mechanical devices such as staplers. TRIZ suggests that one pattern of technological evolution proceeds by transitioning to a microlevel to achieve more universality. In this case this suggested that wound closure might be achieved by a formless liquid or gel, which could take any shape. Another pattern of evolution, increasing
complexity followed by simplification, was applied to the sewing task. The benefits of
sewing and stapling could be combined in a micro-level lattice holding the tissue together.
A next-generation instrument combining these two patterns of evolution is the result—a
reservoir containing liquid polymer with a nozzle connected to a pressure source and
the polymer extruded in a narrow knife-like stream that pierces the tissue and then
solidifies in a continuous V-type lattice form. The new system eliminates needles and
sutures. In this systematic exploration of technologies, many other possible paths of
technological evolution can be examined. It should be noted that TRIZ has aspects of
the morphological approach suggested by Zwicky in the 1940s, but is more normative.

MULTIPLE PERSPECTIVES

One set of tools sweeps in perspectives particularly helpful in analyzing societal/
institutional and individual system aspects. The concept of multiple perspectives on
complex system issues—technical, organizational, personal—arose from the perceived
limitations of systems analysis. Based on the work of Graham Allison [41] and C.
West Churchman [42], it recognizes that “rational behavior” of organizational system
components cannot be assumed to result in rational behavior or optimization of the total
system. The multiple perspective approach to forecasting or assessment, as developed by
Linstone, augments the standard systems analysis perspective, or Technical Perspective
(T), with consideration of the Organizational (O) and Personal (P) Perspectives [43].
Each of these three types of perspective uses distinct paradigms, and provides insights
not attainable with the others. Their synthesis or integration bridges the gap between
the systems analyst or modeler and the real world. It also exposes assumptions that
bias forecasts. This technique has so far been applied chiefly in technology assessment,
but holds great promise for forecasting applications.

COEVOLUTION OF TECHNOLOGY AND ORGANIZATIONAL NETWORKS

There has been an explosion of research on innovation management over the past
two decades, arising from the multiple disciplines of political science, economics, business
administration, and engineering. Techniques used in analyzing the process of innovation
may result in new tools for forecasting. Policy professors Don Kash and Robert Rycroft
have examined complex technological products and processes in six case studies. They
found that all the cases involved coevolution of technology and continually adaptive
private/public organizational networks. As the technology evolved, so did the organiza-
tional arrangements for its use and management. For example the cardio-imaging con-
cept initially involved phased array technology at Hewlett-Packard Laboratories and
Stanford University, then color flow imaging at Duke University Medical Center and
the National Oceanic and Atmospheric Administration (NOAA), then integrated back-
scatter technology at the University of Massachusetts and Duke. In no case did one
organization develop the innovation on its own [44]. The implication is that TF, in handling
complex technological systems, may, like TA, require multiple perspectives to recognize
the coevolutionary setting that will dominate in the new century. This analytical technique
thus has great promise for eventual application to technology forecasting.

SCIENTOMETRICS

This is the study of the structure and evolution of science, and could be a related
source of new models and techniques. A challenge for the future is to find tools that
forecast when specific areas of science can be exploited commercially. This is usually
attempted using expert judgment, either from individual experts or in group processes.
There are few objective or quantitative methods to complement these subjective tech-
niques. Models of the structure of science [45] are being used in industry to forecast when science can be exploited [46]. Forecasts made in 1990 about the scientific developments most important to the pharmaceutical industry correctly identified key developments in genomics and combinatorial chemistry, and were the basis for significant investments by SmithKline Beecham in these areas.

BIBLIOMETRIC ANALYSIS AND DATA MINING

Many new or potential tools have resulted from advances in computer science and information science. Bibliometrics (i.e., counting publications and citations), text mining (profiling literature content), and “Knowledge Discovery in Databases” (KDD) are related ways of eliciting valuable information from electronic information collections, i.e., massive databases [47]. These techniques contribute greatly to technology monitoring, and can be tailored to generate “innovation indicators” [48]. Resulting analyses can profile overall efforts in a given emerging technology: who is doing what, mapping how subtopics interrelate, and yielding trend analyses on publication, patent, citation, or project activity patterns. Other text mining applications can provide “just-in-time” responses to a range of technology management questions. These can benchmark the maturation of the technology, address competitor emphases, track development of standards, locate expertise on particular subtopics, and note sector-by-sector applications. “Discovery” modes can help bridge disciplinary bounds, for example, alert engineers searching for advanced thin-film ceramics for automotive engine applications to the work on such ceramics in microelectronics, or to alert scientists working on a problem to putative factors from other research domains [49].

Consider the system of launching Polaris missiles from nuclear submarines. This required at least four distinct technological breakthroughs: nuclear propulsion systems for the submarine, solid propellant rocket fuel, a precise inertial navigation system, and a heat-resistant reentry nose shield. Both technology transfer and technology fusion were required. In such cases, a technology that has only rarely been mentioned in conjunction with the focal technology may be the clue pointing to an unexpected potential linkage of technologies. Such novel linkages of distinct technologies may well elude conventional TF techniques, but may surface from bibliometric mining of massive electronic data bases. Such techniques may also reveal the possibility of imminent industrial disasters, for example, hidden failure modes, or may point to unintended consequences and impacts.

COMPLEXITY SCIENCE

Advances in computer modeling have allowed the development of complexity science, and it may also lead to new insights and tools for TF. In the 1980s, an interdisciplinary team at the Santa Fe Institute pursued a computer simulation approach to the analysis of complex sociotechnical systems. Such nonlinear adaptive systems are found to exhibit various states: (1) stable, that is, converging to an equilibrium; (2) oscillating stably; (3) chaotic with predictable boundaries; or (4) diverging unstably. In the chaotic state the system appears to show paradoxical behavior: it is deterministic because it is fixed by equations, and yet it incorporates randomness. It may be orderly and suddenly become chaotic, or vice versa. Such systems are exceedingly sensitive to initial conditions, making the use of historical data as a basis for forecast questionable. Behavior is “adaptive” in that each system element reacts not to the whole picture, but to its own internal conditions or models. Each system component must base its “decisions” on local information or conditions, but has the ability, using feedback, to create or revise the models or rules governing its actions.
The total system emerges from the self-organization of its parts, and thus is not
optimizable from the top down, i.e., the rational behavior of system components is not
equivalent to rational total system behavior. Most significant of all is the recognition
of inherent limits of predictability—the chaos phase. In simulations of primitive ex-
change-type economy models with thousands of individual trading elements or agents,
it was found that some foresight on the part of the agents is better than none, but large
amounts of foresight are less “fit” than modest amounts [50]. It is also useful for the
long-range planner to keep another characteristic of complex adaptive systems in mind:
they continually evolve and do not have optimal end states.

This approach has strong implications for TF/TA, especially if, as argued above,
technological innovation increasingly depends on scientific advances, which are based
on self-organizing principles. Some of the implications:

1. It is now recognized that the beginning and end of the familiar S-shaped technol-
ogy growth curves are domains of instability and chaos. This accounts for the
fact that the “take-off” point of an innovation and the shift from one S-curve
to the next present barriers to the forecaster, whereas the smooth stable growth
portion between them is a realm of reasonable predictability. The bifurcation
concept in the chaos theory may also prove relevant in the analysis of innova-
tion patterns.4

2. The role of randomness in innovation is vital; it creates fluctuations that act as
natural seeds from which new patterns and structures grow. It is a point well
known by managers: shake up the organization if you want to foster creativity.
Mapping the domains of stability and chaos may allow deliberate introduction
of chaos into a stable but stagnant system.

3. At times it may be desirable to delay or forestall a phase change. For example,
it may be dangerous to speed up information flow when there is the potential
of inducing chaos that management cannot handle. Cutting feedback loops in
the system can avert inappropriate timing of the onset of chaos. On the other
hand, improving feedback can enhance the agents’ local information, emergent
self-organization, and the bottom-up decision-making process.

4. Modeling may generate insights on critical questions; for example, with today’s
information technology what is the desirable balance between organizational
centralization and decentralization?

CRISIS MANAGEMENT

From multidisciplinary work on decision making in government and in the military,
the concept of crisis management has developed. It, too, may find uses in the practice
of technology forecasting because of the inherent limitations to forecasting capability.
Advancing science and technology are revealing new realms of ignorance and compounding
the difficulties [52]. More surprises and inconceivable events are inevitable, and
training to handle the unexpected must be enhanced. The military train their officers
in many scenarios through war games, not with the expectation that one of these specific
scenarios through war games, not with the expectation that one of these specific scenarios
will materialize, but in the hope that the officers will internalize the ability to react
effectively in an unfamiliar situation. As Karl Popper argues, logically present knowledge

4 The chaotic nature of oscillations in the mature phase of S-curves is discussed previously [51]. It is also
shown that these oscillations can be modeled by a modified set of predator–prey Lotka-Volterra coupled
differential equations.
cannot know the contents of radically new knowledge. Harvey Brooks talks of “the impossibility of proving impossibilities” [53]. For the decision maker, a useful analogy is the task of steering a boat in a turbulent stream. There is only partial control, and the view ahead is often obscured. What is essential are constant alertness and quick reaction, steering clear of looming rapids, rocks, and shore—in other words, catastrophe avoidance [54].

Conclusions

Technology and technological change are both drivers and results of complex interactions in the context of social, economic, and political well-being. Anticipating and understanding the course of technological change is a challenge for decision makers in both government and corporations.

The decade of the 1990s has initiated an upsurge in TF activities under diverse labels, using both old and new techniques. These and other new kinds of TF will be shaped by many social and institutional factors, as discussed above. In the future, who will be the customers for, and users of, TF/TA? For both the private and public sectors, tough economic competition is the primary driver of technological innovation, and, hence, the key motivator to conduct TF. The “technology delivery system” [55] from R&D through organization and customer relationships has evolved from the 1950s until today; forecasting innovation requires recognition of the complex of factors acting upon such systems.

From a large company perspective, innovation increasingly depends on collaboration on aspects ranging from research to product development to customer service. That demands more external information than in the days of greater vertical integration, and will require judicious use of TF to inform technology strategy.

Small companies have traditionally relied on innovativeness to survive. In the early decades of the 21st century, rapid technological change implies that they too need to be technologically informed. In the past, small firms often pled lack of time and resources to invest in luxuries such as TF. There is a need for development of easily comprehensible, timely, and cheap sources of TF for small companies.

New procedures will evolve to facilitate meeting the intelligence needs of a diverse set of technology managers and policy makers, for example, R&D managers, evaluators, intellectual property managers, strategic business unit planners, or product development team builders.

Who will perform TF analyses? In one sense, anyone can do forecasting, because the tools matter less than familiarity with what the users really need to know and how they want it provided. On the other hand, we are increasingly dealing with complex systems where any one individual cannot understand the whole system, let alone its social and environmental setting [44]. Given the complexity of innovation processes and competitive systems, understanding the diverse and increasingly sophisticated tools can elicit critical information from multiple sources. There is, therefore, much merit in revitalizing academic interest in TF, undertaking research to innovate and validate the tools, and providing training in their appropriate use.

The best answer to the question of who should do TF is that all those engaged in the technology delivery system should have a sense of what constitutes valid TF and appreciate what it can do for them. Every scientist working toward eventual innovation, each design engineer, production manager, product developer, and technology marketing professional should become informed on where the related technologies are likely to be heading. This information will pay off in avoiding dead-end initiatives and deadly surprises, and in seizing technological opportunities in the competitive marketplace.
References

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