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FROM MY PERSPECTIVE

From information age to molecular age

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1. The information technology era

The increasingly rapid evolution of technology has defined three successive societies: industrial, information, and molecular. The first took off in the Western societies around 1800 and has passed through its gestation, growth, maturity, and senescence. The second, centered on computers, communications, and networks, took off about 1950 and is maturing. The third, encompassing biotechnology, nanotechnology, and materials science, is in its gestation stage.[1] Just as information technology was built on the foundation of the industrial era, so molecular technology is being built on that of the information technology era.

Indeed, we observe a fading of boundaries or convergence: In the sciences, physics, chemistry, and biology are beginning to blend, and in technology, the separation between infotech and biotech is fading [1]. Some writers suggest that biology is becoming a computer science while others see information technology adopting the characteristics of biological systems. We are even beginning to sense that ultimately the boundary between technological and living systems may blur.

In tandem with the rise of the information society after World War II, two other developments were of great significance, (1) the Cold War energizing the U.S. Department of Defense to act as driver for technology forecasting and (2) the concern with operations and systems analysis. The client for the forecasts was concerned with long lead-time systems but unconcerned with public acceptance or marketing considerations. The combination of (1) and (2) led in the 1950s and 1960s to the development in the United States of forecasting tools, such as trend extrapolation, growth curves, leading indicators, Delphi, relevance trees, scenarios, and needs analysis.

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[1] These phases may be viewed as successive S-curves, each S-curve itself composed, in fractal fashion, of a series of S-curves.

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By 1970, the setting began to change.

(a) The Cold War was waning and the limits of systems analysis were becoming apparent.[2] The nonmilitary private sector took on a greater role in R&D. In this connection, it should be noted there is a striking cultural distinction between the United States on the one hand and Europe and East Asia on the other. "Industrial policy" on the part of the government is disdained in the United States, while it is seen as a useful option elsewhere (e.g., MITI in Japan). This difference is exemplified by

- the rise of "National Foresight Projects" in Japan and Europe, not in the United States and
- the lack of support for the Office of Technology Assessment in the United States.

The upshot was that analysts in Europe and the Far East took on a major role in developing "foresight" concepts. Some U.S. corporations had done analogous work as part of their own planning decades earlier, but usually this work was of a proprietary nature and not widely published. It was always recognized that a technological forecast is only one input to a corporate strategy and that customer needs or markets as well as the political, international, economic, labor, and regulatory environments must be drawn into the planning effort.

(b) The awesome growth of computational power made possible a revitalization of systems research and analysis. The computer became a kind of laboratory tool for the researcher. One example is the development of "complexity science" with the Santa Fe Institute, formed in 1984, becoming a focal point. Over the last two decades, this effort has provided stunning new insights into the nature of the systems we are dealing with today: complex nonlinear, dynamic, adaptive systems (CAS). Their possible state domains (stable, stably oscillating, chaotic with predictable boundaries, and unstable) and their bottom-up evolution and self-organization from the simple to the complex have already taught us much that is highly relevant to forecasting. Two lessons for management will be particularly significant for the next technological era:

1. the clear recognition of inherent limits to forecasting,
2. the ability to use the computer to perform extensive computer modeling to simulate the behavior of CAS as well as to do vast data search and analysis.

The year 1984 also saw the recognition of another facet of complex systems in the information technology era: the difficulty of managing tightly coupled systems that feature intricate interactions[3] [3]. Tight coupling calls for centralized control, but decentralization is preferable for intricate interactions. Systems of this kind may fail with very severe consequences in many ways, although each contributing failure cause has a low probability of occurrence. Their increasing frequency, even in the absence of terrorism, is reflected in the

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[2] It was the recognition of the limits of systems analysis that led to the multiple-perspective concept [2].

[3] Characteristics of tight coupling: process delays and alternative methods not possible; redundancies and substitutions must be designed in. Characteristics of intricate interactions: many feedback loops, multiple and interacting controls, indirect or inferential information.

Three Mile Island, Chernobyl, and Bhopal industrial accidents, the Columbia space shuttle disaster, and the Northeast electric power blackout.

2. Overcoming the inherent limits

The first lesson is a consequence of the understanding of the CAS state domains. We now see the beginning and end of S-curves as fundamentally different from the central portions: the latter denotes stable incremental growth and good predictive capability, the former signifies instability or chaos and unpredictability. As Fig. 1 suggests, an increasing pace of technological change could tilt the balance between realms of stable and unstable, or predictable and unpredictable, growth. These are aspects central to a better understanding of breakthrough or disruptive technologies.

We also have become aware of the fact that small perturbations in initial conditions can result in very large changes in subsequent system behavior (the butterfly effect).

The effect on management could well be profound. Continuous adaptation to change will be necessary for success and this, in turn, requires superior surveillance of the environment

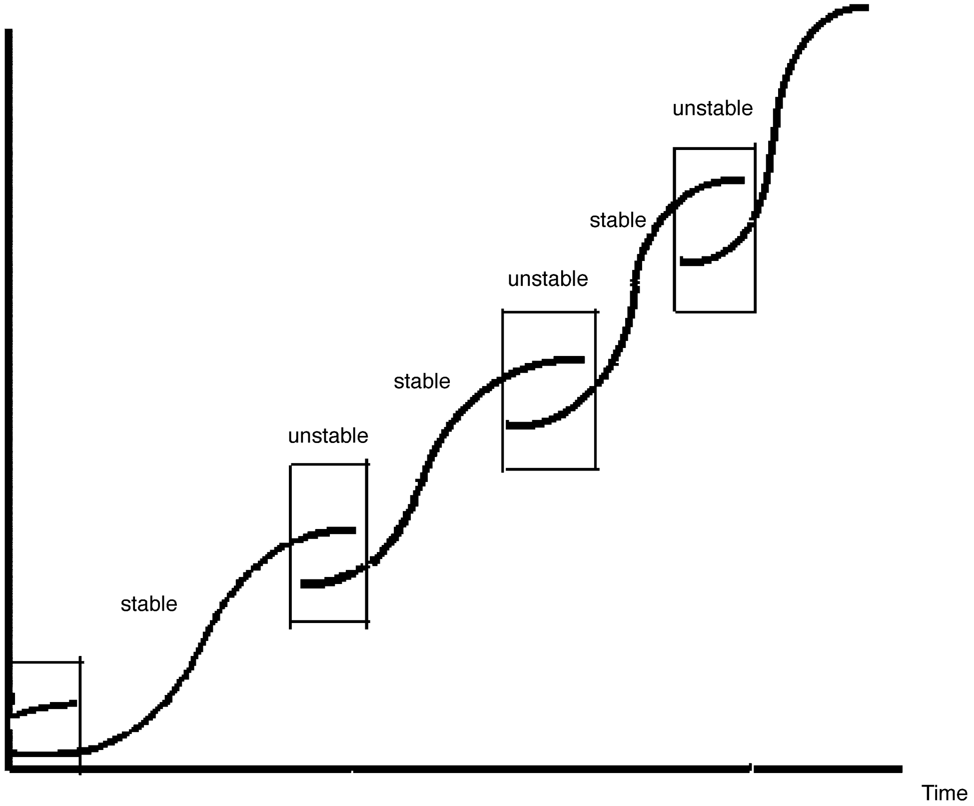

Fig. 1. The molecular era. Will “stable” forecasting domains shrink?

and unprecedented flexibility. Consider, for example, the concept of high reliability organizations (HRO), an effective answer for complex systems that can suffer disastrous accidents as noted in the preceding section. Such organizations are characterized by the ability to shift from vertical (hierarchical) to horizontal (flat) almost instantaneously [2, p. 185]. Reliance on simple rules and bottom-up self-organization rather than firm top-down plans facilitates adaptability to a rapidly changing environment.

Time rather than space is becoming the critical dimension for management. The world has already become a "global village" characterized by simultaneous localization and globalization in the cultural and organizational, as well as the economic, sphere. With time as the key dimension, superior instant sensing, computer data management, and networking will be the norm. We already have witnessed these changes in the management of the Iraq war.

Coalition commanders at forward locations had the ability to

- continuously receive updated precise information on all their own and opposition forces,
- respond rapidly to changing circumstances,
- call in precision air strikes or redirect weapon systems within minutes of receiving new information,
- have analysis of surveillance data performed by experts in U.S. centers 6300 miles away, yet receive their results in the field in minutes,
- call opposition commanders on their cell phones,
- operate effectively with a flattened hierarchy as well as leaner forces, and
- conduct "swarm warfare," i.e., rapid convergence of forces on targets, then rapid dispersal [4].

The rapid development of nanotechnology and other molecular level technologies will further revolutionize management and operations in the military. For example, flexible networks of tiny sensors may form unobtrusive systems that can perform both surveillance of, and response to, chemical attacks [5].

These recent examples underscore the primacy of time over space.[4] We anticipate analogous shifts in business management and operations.

Thus, the first lesson leads to superior sensing, communication, and analysis of information combined with very flexible adaptive organization as one answer to the inherent limits to forecasting.

3. Computer simulation of CAS

Let us now turn to the second lesson, the ability to perform extensive computer modeling to simulate the behavior of CAS. This ability has been developing rapidly in recent years. Cellular automata and genetic algorithms are two of the tools now widely used in this work.

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[4] The German Blitzkrieg, bypassing the Maginot Line in France in 1940, may be viewed as a precursor to this principle.

The modeling combines the use of heterogeneous "agent" populations, simple rules, an environment (e.g., resource distribution), interactions, and feedback based on information locally available to the agents [6]. A 1999 article in *TFSC* dealt with the "growing" of CAS from the bottom up by computer simulation [7]. The article also suggested several ways this approach could draw forth insights relevant to technology planning and management:

- map the domains of stability, stable oscillation, chaos, and instability,
- use this information to stimulate creativity by moving a stagnant, stable system to chaos ("creative destruction") or accommodating management constraints by delaying the chaotic phase (e.g., adding feedback loops in the first instance and cutting them in the second),
- probe the appropriate balance between centralization and decentralization or between globalization and localization [7].

Since then there have been *TFSC* articles on "Using Cellular Automata Modeling of the Emergence of Innovations" [8] and "A Simple Agent Model of an Epidemic" [9]. Recent work by Goldenberg et al. uses a cellular automata model to address the rebirth of extinct innovations [10]. Computer simulation would also be the means to probe the analogy between biological and technological evolution, as Kauffman suggests [11].

The computer can now also be harnessed to overcome the limits to forecasting in another way. We can consider a spectrum of thousands of scenarios to identify, test, and shape near-term actions that can yield robust adaptive policy strategies to move us in desirable directions in the long-term. This process involves a combination of (a) exploratory computer modeling to create a vast ensemble of future scenarios and (b) computer-generated visualization and search procedures to extract information from this ensemble that is useful in weighing alternative decision options. We can even introduce technological surprises and evaluate their impact [12].

In all these tasks, we essentially use the computer to deal with system complexity and uncertainty in ways that would have been unimaginable only a short time ago. This capability should transform our approach to forecasting and foresight.

4. Data search

Besides CAS modeling, we can do vast database searches or data mining, using database tomography and bibliometric analysis. We can perform automated semantic processing of patent and journal texts to detect evolving technologies and possible new linkages among technologies. We can analyze large amounts of textual computerized material to identify promising science directions and opportunities. The database tomography can use algorithms to extract multiword phrase frequencies and do phrase proximity analyses. Bibliometric analysis readily identifies the most prolific authors and most frequently cited journals [13].

We can perform general environmental scanning to identify emerging needs. It will also be possible to test many permutations and combinations of variables in a morphological search for innovations.

The patent database search has made possible accelerated evolution of engineering systems. “Laws of inventive problem solving” and “patterns of evolution” have been extracted from the search. Consider, for example, evolution toward the microlevel, toward decreased human involvement, and toward increased dynamism and controllability. These patterns give rise to “lines of evolution.” Thus, increasing controllability has a line involving four stages from uncontrollability to programmed controllability to semiautomatic control to self-controlled system (say, wire to electrical switch to circuit breaker to reusable fuse). The process, known by the acronym TRIZ, thus generates concepts for the next generation of a technological system[5] [14].

Whereas TRIZ began with a search of a very large patent database, in combinatorial chemistry we search a vast array of molecules to determine combinations that have desirable characteristics. The search mechanisms for genes and proteins pose enormous, now tractable, data scan requirements. The human genome project is creating a data bank of more than 30,000 genes, which, in turn, express the human proteome encompassing the entire complement of millions of human proteins. Biotechnologists and pharmaceutical companies have already recognized the central role of the computer in this context. Whole-genome chips already allow scientists to scan all genes in a human tissue sample at once. Genomics and proteomics will certainly become major areas of activity.

5. The molecular technology era

The molecular technology era is defined by the focus on the molecular scale, with nanotechnology, biotechnology and materials science coming to the fore. We are dealing here with

- self-assembly at the molecular level or programmed molecular factories, for example, to create photonic crystals for data storage and transmission or low-cost, fault-tolerant microprocessors,
- genetic recombination and molecule reprogramming, starting with natural genes to develop new and improved molecules to fit diverse demands,
- embryonic stem cells that can yield medicines to combat life-threatening diseases,
- nutritional genomics and pharmacogenomics, linking genes to diet and to drug response, respectively, to improve human health,
- combinatorial chemistry, creating a vast library of molecules and evaluating them by automated techniques for factors like solubility, stability, and toxicity.

Nanotechnology involves the manipulation and control of matter at the nanometer scale (nano = one billionth). Of particular interest is molecular scale manufacturing, now identified

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[5] Interestingly, both the 1959 Arthur D. Little work on basic research influence (see next section) and the Kostoff et al. work of 2001 [13] were done under the auspices of the U.S. Navy. The initial efforts on TRIZ were undertaken by G. Altshuller in the Soviet Navy.

by the letters MNT. This is done to distinguish it from other applications that are now subsumed under the nanotechnology label.

There is, for example, the new Institute for Soldier Nanotechnologies at MIT, supported by the Department of Defense, DuPont, Raytheon, and Massachusetts General Hospital. The focus will be on nanoscale materials and active nanodevices as well as active self-assembled nanosystems. The Naval Research Laboratory is also pursuing nanotech R&D [15]. Among the applications of interest:

- reduction of the weight of soldiers' packs from 90 to 15 lb,
- night-vision contact lenses,
- machinable ceramic superconductors,
- microfabricated electron sources,
- machine vision for integrated autonomous vehicles.

The molecular technology era is adopting many concepts from biological evolution, such as bottom-up self-organization, emergence, adaptive capability, simple rules, codes, and self-assembly at the molecular level. Can we use the lessons of natural biological evolution to enable us to forecast evolution in a molecular technology era? The new tools—genetic algorithms, neural networks, and molecular programming—reflect the centrality of evolution as the paradigm of this age.

The focus on biology prompts us to recall Casti's mapping in his book *Searching for Certainty: What Scientists Can Know About the Future* of areas of science in two dimensions, explanatory capability and predictive capability [16]. Both evolutionary and developmental biology are graded as "poor" in predictive capability (although the former is rated "good" in explanatory capability). As with its biological precursor, we may find that the predictive capability in molecular technology evolution may well be poor compared to its explanatory capability.

We surmise that the impact of the convergence of information and molecular technologies on forecasting, foresight, and planning may involve significant shifts.

5.1. Technology- to science-based forecasting

The molecular scale focus suggests an increased emphasis on science-based forecasting as we are working at a more basic level. It is admittedly more difficult than technology-based forecasting. Much of science is basic research that is far less connected to clear objectives than applied research. Basic research may be defined as follows:

> Basic research is that type of research which is directed toward the increase of knowledge in science. It is research where the primary aim of the investigator is a fuller knowledge or understanding of the subject under study [17].

The obvious source of information on research is the publication of articles in journals. During the Cold War, analysis of such publications was used by intelligence agencies to forecast the enemy's technological advances. Specifically, sudden cessation of publication in a certain field would suggest that research was leading to application and system development. Data mining is eminently suitable in such an approach.[6]

Nearly a half century ago, Arthur D. Little, Inc., addressed the question of basic research for the U.S. Navy in the highly competitive Cold War setting. Several case studies of the evolution of technology from basic research were performed. One concerned shock wave theory from 1848 to the supersonic aircraft; another examined radar from the work of Oersted, Ampere, and Faraday in the early 1800s and the "Edison effect" in 1883 to World War II. Then there is the importance of one scientist and his "disciples," for example, I.I. Rabi on the field of molecular beams and magnetic resonance [18]. The dilemma is that such analysis is possible in hindsight but exceedingly difficult for foresight purposes.

5.2. Exploratory to normative forecasting

Forecasting has always had two procedural options: (a) start from extrapolating past technological capability ("can do") and then consider the need for the forecast future capability ("ought to do") or (b) start with a future need and then determine how to achieve it. For example, the ICBM was initially proposed based on a perceived capability. On the other hand, the AICBM (or ballistic missile defense system) was seen as a need first at a time when the capability to build it was far from apparent. In all cases there must result interaction and iteration between the "can do" and the "ought to do," between the exploratory and the normative. One suspects that when the creation of custom-tailored new molecules, genes, proteins, and materials becomes feasible, it may be more practical to begin with a need than a vast array of capabilities.[7]

5.3. Forecasting to rapid adaptability and robust planning

We have noted that the relative balance between chaotic and stable growth periods may be tilting to ward the unstable (Fig. 1). This would severely constrain the ability to forecast. Taking a leaf from natural system evolution, it suggests that reduced reliance on system forecasting can be compensated by much greater system adaptability. We have seen in the case of the military how superior surveillance or sensing, high connectivity or networking, rapid information flow and analysis, flexible self-organization (e.g., swarming), and a fine balance between centralization and decentralization can lead to effective adaptability to change. With time rather than space the critical dimension, information technology provides vital support for rapid adaptability.

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[6] The current U.S. Administration's constraints on stem cell research is shifting the work to small private companies that consider the research proprietary and do not publish it in the open literature. This significantly complicates the data-mining task for forecasting.

[7] This does not negate the recent finding that innovation has generally been most successful when it was "taking advantage of random events" [19].

Successful business organizations are likely to have analogous characteristics. This means that unprecedented management adaptability becomes crucial [1]. Technological evolution can be far more rapid than biological evolution. More than ever, uncertainty must be confronted and strategies must be robust rather than optimal. Instant information access, computer capacity, global connectivity, and bottom-up system evolution all facilitate adaptability. For example, the laws of inventive problem solving and lines of technical evolution can be examined to determine possible new configurations. These can then be fabricated at the molecular level. Such innovations can be tested in social system agent-based simulation models to evaluate their diffusion and impact. Surveillance of computer databases will alert managers to surprise developments, new opportunities as well as failures, with minimum delay. Then rapid action can exploit openings, allow course corrections, and let management embark on new paths.

For the longer term, management will have the means to replace planning based on questionable forecasts with robust strategies based on effective interaction with large computer-generated scenario ensembles. Thus, the inability to predict the ramifications of the 21st century technological revolutions need not inhibit effective actions.

The implication is evident: the convergence of information and molecular technologies may well revolutionize the innovation process and transform not only the role of forecasting, but also the process of foresight and planning. Indeed, directed technological evolution can take on a whole new meaning.

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