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Three eras of technology foresight

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ABSTRACT

Technology has molded the industrial and information societies and will mold the molecular society of the future. The latter will encompass nanotechnology, biotechnology, and materials science. It will also lead to unprecedented convergence in the sciences and technologies. This discussion considers the unique impacts on technological forecasting and foresight accompanying each of the three societies.

1. Introduction

The increasingly rapid evolution of technology following the Agricultural era has defined three successive societies: industrial, information, and molecular (Fig. 1). The first took off in the Western societies before 1800 and has passed through its gestation, growth, maturity, and senescence. The second, with its roots in World War II, centered on computers, communications, and networks, took off about 1970. It is now focusing on digitalization as it moves to maturity in the first quarter of the 21st century. The third, encompassing biotechnology, nanotechnology, and materials science, is only in its gestation stage now. This evolution is also effecting convergence in science and technology (Meyer and Davis, 2003). One example is combinatorial chemistry, creating a vast library of molecules and evaluating them by automated techniques for factors such as solubility, stability, and toxicity. Bioinformatics involves mathematics, informatics, statistics, computer science, and artificial intelligence, as well as chemistry and biochemistry, to address problems on the molecular level.

2. The first era

Turning to technology forecasting, this field had its roots in the industrial era with the work of Frederick W. Taylor, known as the father of scientific management. His book "The Principles of Scientific Management" was published in 1911. In World War II mathematics was successfully applied to military problems such as intercepting enemy bombers and searching for enemy ships (i.e., operations research). The war also made clear that advanced technology would in coming decades assume an unprecedented importance for national security as well as spectacularly boost defense budgets. Systems analysis became a critical tool in designing new systems while the complexity of the systems under development meant long lead times and long planning horizons. Technological forecasting thus became a necessity in evaluating future US defense needs.

In the 1950s and 1960s quantitative tools were developed by the Department of Defense and its contractor organizations. These ranged from trend extrapolation (e.g., Moore's Law) to measures of technology and growth models. Semi-quantitative methods included mapping, morphology, and needs analysis. Predominantly qualitative approaches encompassed scenario writing and group processes such as Delphi, developed at think tanks like The RAND Corporation. It should be noted that pioneering work in a morphological approach to invention was developed at the same time in the Soviet Union. It also became apparent that the impact of new technologies, i.e., technology assessment, had to be addressed.

By 1970 the setting began to change. The Cold War was waning and the next major threat, terrorism, galvanized by Islamic fundamentalism, has not led to the articulation of a national technological innovation drive as did the Soviet atomic weapons and Sputnik in the 1950s.

By 1970 the limits of systems analysis were also becoming evident. "Assumption drag" was a frequent problem, implying the use of assumptions reasonable at present for a future where they were no longer valid. Often the maxim was: "pile up an imposingly complex system of equations and then subject them to an analysis of ineffable innocence" (Berlinski, 1976, p. 83). In the words of Hoos (1979):

In our technological era, the dominant paradigm is so technically oriented that most of our problems are defined as technical in nature and assigned the same treatment – doctoring by systems analysts. The 'experts' are methodological Merlins...Most of the technology assessments I have reviewed…must be taken with a large measure of skepticism lest they lead us to regrettable, if not disastrous, conclusions.

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The nonmilitary private sector took on a greater role in R&D. In this connection we observe a striking cultural distinction between the US on one hand and Europe and East Asia on the other. ‘‘Industrial policy’’ on the part of the government was disdained in the US, while it was seen as a useful option elsewhere (e.g., MITI in Japan). This difference was illustrated by:

The rise of ‘‘National Foresight Projects’’ in Japan and Europe, not in the US.

The lack of support in the US. for the Congressional Office of Technology Assessment.

The upshot was that analysts in Europe and Asia took on a major role in developing ‘‘foresight’’ concepts. This shift is clearly reflected in the national affiliations of authors in the journal *Technological Forecasting and Social Change*, which was founded in 1969: in the early years most authors were American; in 2005 and 2006 less than a third were. The shift is similarly evident in *Technological Forecasting and Social Change* subscriptions: in 1974 US 51%, Europe, Asia, and other 49%; in 1999 US 34%, Europe, Asia, and other 66%. Incidentally, the term foresight, more inclusive than forecasting, was increasingly used, particularly in the UK.

Some US 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 clearly 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 total foresight effort. It was not always apparent that technical experts tend to be too optimistic in the short-term, failing to appreciate implementation problems, and too pessimistic in the long-term, failing in their imagination with regard to major impacts and new solutions.

8000 BCE The Agricultural Society

1800 CE The Industrial Society –
spawned the First Foresight Era

ca. 1970 The Information Society
Computers
Communications
Networks
spawned the Second Foresight Era

ca. 2025 The Molecular Society
Biotechnology
Nanotechnology
Materials Science
spawns the Third Foresight Era ?

Fig. 1. Societies and foresight eras

3. K waves

The year 1970 also has particular significance in connection with Kondratiev waves (often termed K waves or long waves) of 50–60 year duration. Since about 1800 a cyclical pattern has been observed not only in economic prosperity–recession–depression–recovery, but also in technological innovation clustering, primary global energy sources, and corporate organization. For each wave, measured from one peak to the next, there is an overarching technology (Fig. 2). The recovery-prosperity upswing is a time for economic growth, consolidation of knowledge, and exploitation of available technologies. The subsequent recession–depression downswing is not only a period of economic decline but, in Schumpeter’s terms, one of ‘‘creative destruction’’, an intensifying pace of innovations, culminating with a burst of innovations in the depression. For example, radar, television, helicopters, nylon, jet engines, and computers formed an innovation cluster with the center point 1937. Preceding center points were 1828 and 1880 (Marchetti, 1980). Each such cluster frees a stagnating economy and creates a vibrant new economic environment galvanizing the next K wave upswing, a ‘‘knowledge consolidation’’ phase. As has been suggested, the pattern has ramifications in other domains. It is possible that biological rhythms underlie the K waves, each upswing or downswing corresponding to one generation (25–30 years). If this is the case, biotechnology may well alter the K wave pattern in the future.

4. The second era

The first era of technology foresight corresponds to the 4th K wave upswing. We identify the second era by its overarching technology – information (IT) – encompassing the 4th K wave downswing and the 5th K wave upswing. Thus Devezas et al. (2005) shows the internet evolving as an innovation in the 4th K wave downswing. Table 1 illustrates the remarkable impact of this technology in effecting simultaneous centralization and decentralization, or globalization and localization. For forecasting an obvious development has been the exploitation of the vastly expanded computer/communications capabilities.

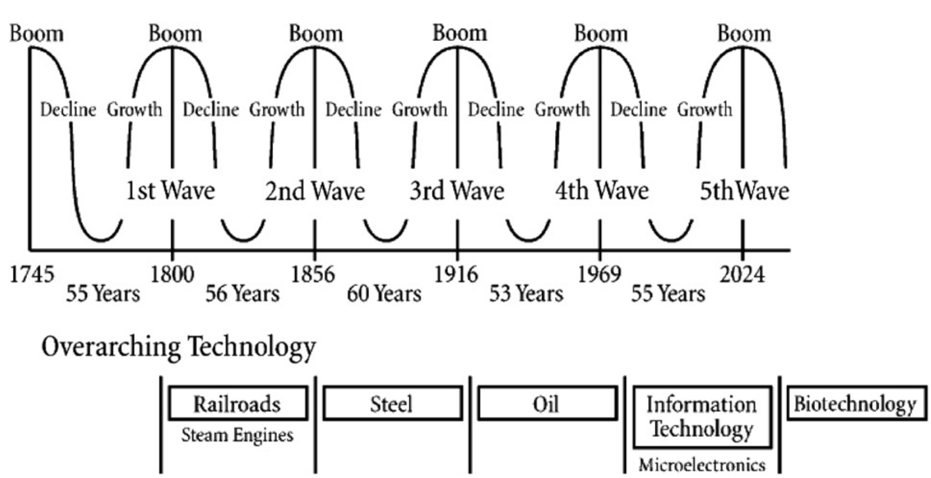

Fig. 2. Long wave or K wave cycles.

Table 1
The impact of information and communication technologies: unprecedented decentralization and centralization.

	Decentralization	Centralization
Communication	Desktop publishing, blogs	CNN, giant media conglomerates
Governance	Tribalism, ethnic enclaves	Integration (European Union)
Conflict	Insurgency, terrorism "Everyman" as Faust	Global terrorism networks
Religion	Small sects	Quasi-global Islamic nation
Corporation	Flat (non-hierarchical) local control product customization ("The Long Tail")	Hierarchical central control global corporation McWorld

We consider just two examples, involving the two most widely applied techniques, the Delphi method and scenarios. The former is the iterative procedure originally developed to query experts over several rounds until stability in the responses is attained, all the while maintaining the respondents' anonymity. Today real-time Delphis are made possible using the internet. Other examples of the evolution of Delphi as a powerful tool to communicate, coordinate, and collaborate, suggest that this era may become a true Age of Participation (Linstone and Turoff, forthcoming).

The computer can now also be harnessed to overcome the limits to forecasting in another way. RAND has considered 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 (Lempert et al., 2003)

Recent work (Burt, 2007) seeks to relate scenario development to the identification of disruptions and discontinuities using directed graphs or digraphs found in systems theory. An example of a disruption is the shift from propeller to jet aircraft; there is a major subsystem change but the system itself (aircraft) remains stable. A discontinuity involves a fundamental system transformation, for example, the shift from silver halide photographic film to digital photography caused a sudden upheaval in the industry. Positive (reinforcing or amplifying) loops in the system can help to identify potential discontinuities.

The current computer capabilities also enable us to search vast data bases, that is, perform data mining, database tomography, and bibliometric analysis. We can do 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. Database tomography is an information extraction and analysis system, which operates on textual databases. Bibliometric analysis readily identifies the most prolific authors and most frequently cited journals (Kostoff et al., 2001). We can perform general environmental scanning to identify emerging needs.

It has become possible to test many permutations and combinations of variables in a morphological search for innovations. The patent data base search has facilitated accelerated or directed 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, developed in the Soviet Union and known by the acronym TRIZ, thus generates concepts for the next generation of a technological system (Clarke, 2000).

Whereas TRIZ began with a search of a very large patent data base, 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.

In all these tasks we essentially use the computer as a laboratory tool. Its speed means that we can perform thousands of runs rapidly and this profoundly affects how we address forecasting and foresight. Another new direction is the adaptation of the 3-D printer to serve not only in manufacturing but, with the availability of an abundance of software programs, to make customized designs and models readily accessible to the innovator. (New York Times, 2010).

During the 4th K wave downswing the foundation has also been laid for new foresight tools. In particular, complexity science and the multiple perspective concept have proven to be significant.

4.1. Complexity science

Systems research has been revitalized by the work on "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 phase states (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. For example, the total system is not the sum of its parts; it has unique behavioral characteristics that cannot readily be determined from those of its components. Such systems may be orderly and suddenly become chaotic, or vice versa. This behavior implies inherent limits to predictability. CAS are exceedingly sensitive to initial conditions, making the use of historical data as a basis for forecasting problematical at best. Small perturbations in initial conditions can result in very large changes in subsequent system behavior (the butterfly effect). Adaptiveness means that each system element cannot see the whole picture but has its own internal models, that is, its own perspective. It must base its decisions on local information, but has the ability, using feedback, to create or revise the models governing its actions. The total system emerges from the self-organization of its parts and thus is not optimizable from the top down. In simulating primitive exchange-type economy models with thousands of individual agents, it is 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 (Epstein and Axtell, 1996, p. 129). We now recognize that the beginning and end of the ubiquitous logistic or growth *S*-curve is a period of chaos. The predictability of the central portion of the *S* curve contrasts with the unpredictability at its beginning and end. An accelerating pace of technological change may tilt the balance between realms of stable and unstable, or predictable and disruptive growth Fig. 3).

Cellular automata modeling has also yielded interesting insights. Consider the recent research papers on "Using Cellular Automata Modeling of the Emergence of Innovations" (Goldenberg and Efroni, 2001), "A Simple Agent Model of an Epidemic" (Gordon, 2003) and "Inevitably Reborn: The Reawakening of Extinct Innovations" (Goldenberg et al., 2004).

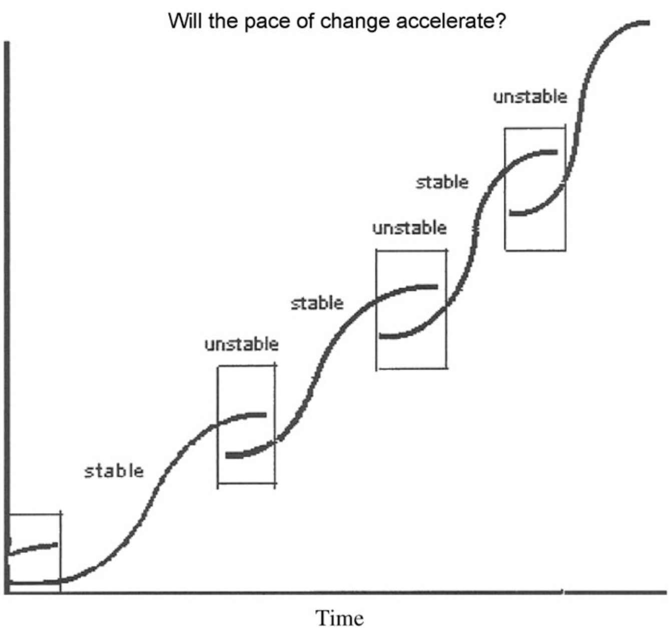

Fig. 3. Stable and unstable phases in technology growth. The ordinate indicates technological capability.

Knowledge of the CAS phase or domain boundaries, "the edge of chaos", can be very useful. Schumpeter's "creative destruction" can be stimulated by expediting the onset of chaos. Inability or unreadiness to manage change can be eased by delaying a phase change, say, by cutting feedback loops.

4.2. Multiple perspectives

Two books published in 1971, Churchman's *The Design of Inquiring Systems* and Allison's *Essence of Decision*: *Explaining the Cuban Missile Crisis*, as well as my own experience in corporate planning, suggested a means to bridge the glaring gap between traditional systems analysis and the real world. Specifically, two perspectives were introduced to augment the systems analysis approach in examining a complex system (Linstone, 1984, 1999). The traditional approach is labeled as the technical or T approach; the added ones are the organizational/institutional (O) and the personal/individual (P). Each uses distinct paradigms and sweeps in insights not attainable with the others (Table 2). Together they provide a much better basis for planning than the T perspective alone. They are particularly valuable in identifying the differences in assumptions underlying forecasts and frequently biasing them. Attention to the O perspective will also make it much more likely that the institutional changes that must often accompany technological changes to make them effective will not be ignored. The T–O–P concept underscores an insight derived in complexity science about adaptive systems noted above, namely, that each system element does not see the whole picture but must rely on its own internal models, that is, its own perspective. In other words, 'rational' organizational (O) or individual (P) behavior is by no means equivalent to the rational technical perception (T) of the system (and its optimization).

Subsequently a fourth perspective, the religious/mythological (R), was added. One way to view the perspectives is seen in Fig. 4:

Table 2
Characteristics of the multiple perspective types.

	Technical (T)	Organizational (O)	Personal (P)
Worldview	Science-technology	Unique group or institutional view	Individual, the self
Objective	Problem solving, product	Action, process, stability	Power, influence, prestige
System focus	Artificial construct	Social	Genetic, psychological
Mode of inquiry	Observation, analysis: data and models	Consensual, adversary bargaining and compromise	Intuition, learning, experience
Ethical basis	Logic, rationality	Justice, fairness	Morality
Planning horizon	Far (low discounting)	Intermediate (moderate discounting)	Short for most (high discounting for most)
Other descriptors	Cause and effect	Agenda (problem of the moment)	Challenge and response, leaders and followers
	Optimization, cost-benefit analysis	Satisficing	Ability to cope with only a few alternatives
	Quantification, trade-offs	Incremental change	Fear of change
	Use of probabilities, averages, statistical analysis, expected value	Reliance on experts, internal training of practitioners	Need for beliefs, illusions, misperception of probabilities
	Problem simplified, idealized	Problem delegated and factored, issues and crisis management	Hierarchy of individual needs (survival to self-fulfillment)
	Need for validation, replicability	Need for standard operating procedures, routinization	Need to filter out inconsistent images
	Conceptualization, theories	Reasonableness	Creativity and vision by the few, improvisation
	Uncertainties noted	Uncertainty used for organizational self-preservation	Need for certainty
Criteria for "acceptable risk"	Logical soundness, openness to evaluation	Institutional compatibility, political acceptability, practicality	Risk aversion
Scenario typology	Probable	Preferable	Possible
• Criterion	Analysis (reproducible)	Value (explicative)	Image (plausible)
• Orientation	Exploratory (extrapolative)	Normative (prescriptive)	Visionary
• Mode	Structural	Participative	Perceptual
• Creator	Think-tank teams	Stakeholders	Individuals
Communications	Technical report, briefing	Insider language, outsiders' assumptions often misperceived	Personality, charisma desirable

O and P deal with humans, collectively and individually, while T and R are constructs created by humans.

5. The third era

The technology era beginning with the 5th K wave downswing (Fig. 2) is defined by the focus on the molecular level, with nanotechnology, biotechnology, and materials science coming to the fore. It is also referred to as the Nanobiotechnology era and the Micro- and Nanotechnology era or MNT (Kautt et al., forthcoming), sweeping in Microelectromechanical Systems (MEMS). Nanotechnology specifically refers to the manipulation and control of matter at the nanometer scale (nano = one billionth). It is made possible by the advance in magnification – from 1000 × in the 1930s to 100 million × in the 1990s. Table 3 offers a comparison with the preceding era. Just as the information technology era (IT) was built on the foundation of the industrial era, so the molecular technology era (MT) is being built on that of the information technology era. Ray Kurzweil (2005) envisions that nanotechnology will lead to a vast increase in computational power and intelligence.

We also see increasing evidence of convergence. Some writers assert that biology is becoming a computer science; others see information technology adopting characteristics of biological systems. As science progresses, the boundary between living and nonliving systems, and between real and virtual life is clearly becoming indistinct. Moravec (1998) suggests that computers will match human brainpower in the 2030s and Kurzweil (2005, p. 136) believes that by 2045 "the non-biological intelligence created...will be one billion times more powerful than all human intelligence today". For a recent survey see Baum (forthcoming).

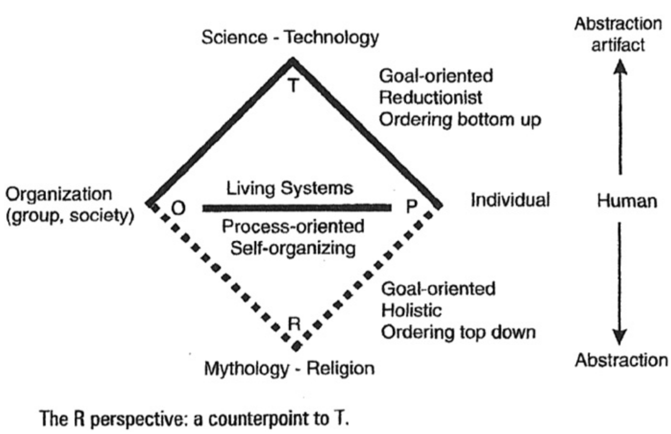

Fig. 4. A schematic of the multiple perspective concept.

The primary reasons for convergence are (1) the trend to deal with entities, such as molecules, that are basic building blocks of all systems, and (2) the use of codes or coded instructions (binary, genetic) in both information and molecular technologies. The tools used by both show the commonality. For example, genetic algorithms provide a probabilistic search procedure based on the Darwinian principle of natural selection; genetic programming applies genetic algorithms to possible computer programs and has been described as an automated invention machine.

The convergence phenomenon is already reflected in at least the following areas:

science–technology
Pharmaceutical product development often draws directly on scientific papers.
biology–chemistry–physics–computer science
All may use genetic algorithms, neural networks, and molecular programming and reprogramming. Bioinformatics and combinatorial chemistry illustrate the convergence in the sciences.
information technology–nanotechnology–biotechnology–cognitive science
Neuropsychiatric research may lead to nanoparticles coursing through the brain, providing new insight on how the brain processes information and identifying possible blockages. Biocomputers may be implanted to serve as "molecular doctors". Genetically modified crops constitute another clear case of convergence (Das, 2007).

Two of the most intriguing implications are:

specificity
molecular technology, exemplified by genomics and proteomics, leads to custom tailored drugs and sensors, as well as custom designed materials of all kinds,
engineering for the human mind as well as body
together with information technology, molecular technology should lead to prostheses that significantly extend human capabilities.

We are dealing here with subjects such as:

microelectromechanical systems (MEMS) that achieve complex functionality in tiny, cheap portable packages, for example, "labs on a chip",

Table 3
A comparison of information and molecular eras.

	4th K wave peak to 5th peak	5th K wave peak to 6th peak
Overarching technologies	Information Communication	Nanotechnology Biotechnology
Major paradigm shift	Time as critical dimension	Molecular scale
Management	Globalization-localization Virtual corporations	Molecular economy enterprise
Energy source	Chemical	Molecular
Intelligence	Information networks Internet as parallel universe	Nonbiological intelligence Nanobots Molecular computing
Industrial commodity	Silicon, software	Nanomaterials
Weapons of mass destruction	Nuclear Chemical Biological	Genetic Nanotechnological Robotic

self-assembly at the molecular level or programmed molecular factories to create desired material attributes and photonic crystals for data storage and transmission,

genetic recombination and molecule reprogramming, starting with natural genes to develop new and improved molecules to fit diverse demands,

in vitro construction of artificial human organs,

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,

nanoscale materials, active nanodevices for manipulation inside cells, nanomachines inside the body for therapy and diagnosis,

active self-assembled nanosystems for military purposes.

For these and other envisioned developments in nanobiotechnology see Hauptman and Sharan (2005).

The US Department of Defense is supporting applications such as night vision contact lenses, machinable ceramic superconductors, microfabricated electron sources, and soldiers' pack weight reduction. A recent survey (Kautt et al., forthcoming) has located 80 Micro- and Nanotechnology Science and R&D Centers in 17 countries, including 33 in the US, 11 in Germany, and 8 in Korea.

Of growing concern are possible adverse effects involving particles at the molecular level. For example, buckyballs, a spherical form of carbon, can enter the brain of fish and cause extensive damage. They raise questions about the health and environmental effects of synthetic nanoscale materials. The "precautionary principle", insisting on proof that an innovation will cause no harm, has gained a significant following in Europe and can seriously retard the development of molecular technology.

This era is adopting many concepts from complexity science and biological evolution, such as emergence, adaptive capability, and bottom-up self-organization with simple rules and codes. 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 (Casti, 1990). 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.

From the "human genome on a chip" to swarming behavior with emergent "smart mobs" joining rapidly in temporary groupings for designated activities, the forecaster will confront a new setting. The convergence of information and molecular technologies on scoping forecasting, foresight, and planning may involve significant shifts. How can we assure that the "experts" and other participants represent the convergent reality and not the "old" discipline orientations? Any discussion of future methodological advances is inherently speculative. We can only suggest what might sprout from some of the seeds planted in the fourth K wave downswing.

5.1. Technology-based to science-based forecasting

In 1997, for example, the majority of patents in the pharmaceutical industry already cited at least one peer-reviewed scientific article. The molecular scale focus suggests an even greater 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, which is far less connected to clear objectives than applied research. Basic research may be defined as that type of research which is directed toward the increase of knowledge in science, where the primary aim of the investigator is a fuller knowledge or understanding of the subject under study.

The obvious source of information on research is the publication of papers 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. Political pressure to constrain 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.

Half a century ago, Arthur D. Little (1959), addressed the question of basic research for the US 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 in the field of molecular beams and magnetic resonance. The dilemma is that such analysis is possible in hindsight but exceedingly difficult for foresight purposes.

5.2. Traditional to biology-based forecasting methods

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 as well as the convergence phenomenon.

Kauffman (1995) has raised an intriguing question suggested by the simulation approach to biological system evolution: can artificial technological worlds be created in the same manner, obeying the same laws?

He writes:

Fundamental innovations are followed by rapid, dramatic improvements in a variety of different directions, followed by successive improvements that are less and less dramatic…If the economy is a web, as it surely is, does the structure of that web itself determine and drive how the web transforms? If so, then we should seek a theory of the self-transformation of an economic web over time creating an ever-changing web of production technologies. New technologies enter (like the car), drive others extinct (like the horse, buggy, and saddlery) and yet create niches that invite still further new technologies (paved roads, motels, and traffic lights)…If the patterns in early stages of a technological trajectory…are tried until a few dominant designs are chosen and the others go extinct, might it also be the case that the panorama of species evolution and coevolution, ever transforming, has its mirror in technological coevolution as well?...Organismic evolution and coevolution and technological evolution and coevolution are rather similar processes of niche creation and combinatorial optimization. (Kauffman, 1995, pp. 192, 281–281).

5.3. Exploratory to normative forecasting

The forecasting process has always had two procedural options:

start from extrapolating past technological capability ("can do") and then consider the need for the forecast future capability ("ought to do"), or start with a future need and then determine how to achieve it (sometimes termed backcasting).

For example, the ICBM was initially proposed on the basis of 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 (and still is). 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 most practical to begin with a need rather than a vast array of capabilities. This does not negate the recent finding that innovation has generally been most successful when it was "taking advantage of random events" (Goldenberg and Efroni, 2001).

A word of caution is in order. One may be tempted to seek a market survey to determine a future need, but that may prove futile. In many cases a need is not widely recognized and appreciated until the technology in the form of a new product is at hand. A market survey of computer needs in the late 1940s and 1950s would have yielded misleading results, as the market envisioned was confined to scientific and technical applications. The pioneers often fail to see the long-term revolutionary impacts of their innovations.

5.4. Forecasting to rapid adaptability and robust planning

Consider for a moment the Roman Empire in the 2nd century CE. A forecaster for this technologically advanced superpower would hardly have forecast its decline and the subsequent Dark Age. We must recognize that *surprises are inevitable*, *and uncertainties are inherent in the foresight process*. The most glaring factor confronting the forecaster grappling with the Third era will be the unprecedented sources of surprise and irreducible uncertainty, often referred to as "wild cards". Incidentally, recent historical analysis suggests that the Roman Empire was brought low not only by barbarian attacks but by the plague which may have killed up to 30 million people.

Today's industrial catastrophes such as Three Mile Island, Chernobyl, Bhopal, the *Exxon Valdez* oil spill, and the BP Gulf of Mexico oil well explosion all are energy-related. As the global population increases and the standard of living in many parts of the world rises, more energy will be inexorably be processed and moved, raising the likelihood of such accidents. In some cases a preventable catastrophe does not reach the threshold of popular alarm, and thus timely action, due to its slow buildup. Examples are ocean pollution and global warming. Pollution equivalent to the *Exxon Valdez* spill, 10.9 million gallons, is released in the world's oceans every eight months. There is also growing concern about possible environmental climate megachanges in the biosphere. History yields evidence of sudden large-scale spurts of change, termed "punctuated equilibrium".

The 21st century is opening with a global war against the West led by fundamentalist fanatics of the "Islamic nation". We now face the possibility of nuclear, biological, and chemical warfare systems (NBC) as well as cyberterrorism. In the future these may be augmented by genetic, nanotechnology, and robotic systems (GNR) as well as space systems. Some of these can be made available to, and used by, non-state groups and individuals. It is a striking characteristic of the evolving technologies that they can magnify the power of the individual enormously. We are entering an era in which "Everyman" can become a remarkably powerful "Faust". (Linstone, 2003).

How can one prepare better for technological surprises? How can foresight effectively counter complacent management? We have already alluded to RAND in connection with its new scenario approach, known as long-term policy analysis (LTPA). It rests on the claim that predictions need not constitute a necessary precursor to effective action. It seeks to draw forth near-term actions that shape the options for future generations rather than determine optimal strategies.

The concept of crisis management also provides a useful approach. The recent industrial catastrophes as well as counter-terrorism have led to efforts to prepare organizations in both public and private sector to respond more effectively. One approach is the fluid high reliability organization (HRO), which has unique characteristics such as the ability to shift quickly from a vertical to a horizontal structure, an uncommon sense of personal responsibility, drills held frequently and evaluated according to very high standards (Linstone, 1999, p. 185).

Compounding the problems are the misperceptions associated with probability considerations. Probability is highly counter-intuitive as many studies, such as those of Tversky and Kahneman (1974), have shown. Events that exhibit very low probability but very severe consequence cannot be handled by traditional expected value calculations. We recognize that intelligent behaviors and decisions are not necessarily "rational" ones. The multiple perspective concept is helpful in dealing with some of these misperceptions (Linstone, 1999).

In complex adaptive systems random appearing events may not actually be random, whereas perceived patterns may be produced by chance. Another problem, discussed extensively by Gould (1996), is the common focus on averages when outliers may be more significant. Complexity science suggests that the relative balance of chaotic to stable growth periods may be tilting toward the unstable (Fig. 3). This would also 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. Indicative of the convergence paradigm, it is information technology, making time the critical dimension, that becomes the key to a quasi-biological process. 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 (Table 2) should facilitate effective adaptability to change.

Successful business organizations are likely to have analogous characteristics. This means that superior management adaptability becomes crucial (Meyer and Davis, 2003). 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. 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.

Finally, let me note that this discussion views the Third era largely from the technical perspective. It will undoubtedly be strongly affected by drawing in the organizational/institutional and personal/individual perspectives.

6. Conclusion

In summary, I would like to raise a number of questions which, I hope, will stimulate thought and discussion.

Will the electorate support the costs inexorably associated with the shift to the molecular age? There are major costs implied, involving educational and infrastructure retooling. These are long-term investments and their critical importance tends to be discounted by voters and their chosen legislators who focus on short-term needs. This effect is particularly strong in an environment of a heavy national debt burden.

The internet is exerting enormous impact on the social and cultural institutions in the 5th K upswing. Will the molecular age have a similarly striking impact and will this alter the K wave pattern? Recall that biological determinants are associated with K waves.

Traditionally military establishments plan to fight the last war over again with better weapons. But the weapons of the information plus molecular era may be highly unconventional—consider the implications of cyberwarfare, perception manipulation via the internet, as well as viral diseases, genetic mutations, and molecular assembly of micromachines. Cyberwarfare is already giving clues as to what may be in the offing in coming decades. For example, stuxnet is a software worm that infects and disrupts specific industrial control systems and apparently has been used (The Economist, 2010). How can effective tools be created to counter terrorists while protecting noncombatants? Note that there does not exist today a national high priority megaproject to deal with 21st century threats, comparable to the Manhattan Project in World War II and the Apollo Project in the Cold War.

How will the new era with its IT-MT convergence and complex adaptive system attributes (edge-of-chaos, bottom up evolution, etc.), as well as new tools (genetic algorithms, agent-based modeling, etc.) reshape economic thinking and corporate management?

Can religious or other ideological movements propel this age in a very different direction? Notice that questions 4 and 5 turn our attention to the O and P perspectives, the latter even to the R perspective (see Fig. 4).

One implication of this discussion is crucial for technologists: the convergence of information and molecular technologies may well revolutionize the innovation process and transform not only the role of technological forecasting, but more generally the process of foresight and planning. Indeed, directed technological evolution can take on a whole new meaning.

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