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An International Journal

Special Section
Honoring Joseph F. Coates

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Forecasting the diffusion of photovoltaic systems in southern Europe: A learning curve approach

D. Spreng
Technology assessment: Impact of high-tech engineering research on energy consumption

Best *TFSC* Paper Award—2002

As in previous years Elsevier Science Inc. is offering a prize of $1,000 to an outstanding paper published in 2002 in this journal in one of the following categories:

- an original contribution to the methodology of technological forecasting or impact assessment, or
- an effective case study of an innovative application of technological forecasting in corporate strategic planning or industrial restructuring.

A Prize Committee, drawn from the Advisory Board, has been formed to undertake the evaluation and the winner will be announced in the March 2003 issue of this journal. The judges' decision will be final.

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Technological Forecasting and Social Change

Introduction

Honoring Joe Coates

Harold A. Linstone
Editor-in-Chief

It is both a real pleasure and a privilege to honor Joseph F. Coates, eminent futurist and longtime member of our TFSC Advisory Board. I first met Joe 40 years ago, when we were both at the Institute for Defense Analyses (IDA) in Washington, DC. Joe immediately impresses, first by his towering physical stature, then by his articulate, knowledgeable and stimulating comments on a remarkably broad spectrum of subjects.

He has the rare talent of viewing any subject from a fresh perspective and leading his listener to open his or her mind. He is critical and does not suffer fools gladly; indeed, he can effectively deflate the pompous and ignorant with suave elegance. Not surprisingly, this has made him some enemies. But his many friends, of whom I count myself as one, can attest to his warmth. He has been an ideal contributor to TFSC with his many "From My Perspective" columns and a collection of excerpts in this issue reflects his sharp wit in dealing incisively with many issues concerning the future.

Joe studied at Brooklyn Polytechnic Institute, Penn State, and the University of Pennsylvania. He started his career as an industrial chemist at Atlantic Refining Company. After IDA, he spent many years at the National Science Foundation as program manager of Research Applied to National Needs. He was an ideal evaluator of projects, homing instantly on weak points and offering valuable constructive suggestions. He also served as assistant to the director and head of exploratory research in the Congressional Office of Technology Assessment. In 1979, he founded his own futures research organization. J. F. Coates, Inc., which became Coates & Jarratt, Inc. in 1992. He has consulted with 45 of the Fortune 500 companies and many smaller firms, professional and public interest groups, and all levels of government. He is a sought-after speaker and lectures to about 50 groups throughout the world each year on trends and future developments. As an example, his lectures on scenarios for 2025 at the World Futures Society have been standing-room-only sessions. He is the author of over 300 articles, chapters, papers and other publications. He also holds 19 patents.

Joe has received much recognition, including an honorary doctorate in 1985 from the Claremont Graduate School. He is a Fellow of the American Association for the Advancement of Science and is listed in Who's Who in America. His wife Vary, a fine researcher and

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technology assessment analyst in her own right [see TFSC vol. 67 (2001), pp. 1–18], has not only been a loving life companion, but a valued critic, sounding board and support.

In the following pages some of his friends and co-workers offer reminiscences and contribute essays in Joe's honor. They include Robert Ayres, Graham Molitor, Andy Hines, Michel Godet, and Art Shostak. Another friend, Don Kash, has a paper in this issue as well. The special section concludes with excerpts from Joe's own wide-ranging "From My Perspective" columns over the last 12 years.

We wish Joe many more years to challenge and stimulate us!

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On Coates, Information technology and future employment

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I tried to get out of this. Truly. I thought I had nothing new to say 'off the shelf' as it were. At least nothing worthy of publication in this journal. But having known Joe Coates since 1970 or so, and Hal Linstone even longer, I guess an easy escape was not in the cards. I cannot believe that 32 years can pass so quickly.

I first encountered Joe as a first-time NSF proposal awardee (is that a word? It is now). Joe was project officer. That was 1970, as near as I can recall, and I don't intend to go look it up. I thought he was a tough task-master at the time. I realize now he was a pussycat. We started out trying to do much too much, and he could easily have justified an early retirement of our project. He didn't do that, and thanks to his patience and guidance, we changed direction and did some interesting things during the second and third years. The end result was something we called the material–process–product model, and it was a precursor for mass flow analysis, substance flow analysis, life cycle analysis, and a lot of the other tools that now cram the toolbox of "Industrial Ecology." Thanks, Joe.

I think I next encountered Joe at meetings of the World Future Society, where we were both founder members and regulars at meetings. Then he went to work as an assistant to the director of the newly created Office of Technology Assessment (where Vary also got a job). For a few years we didn't cross paths much, though I recall attending a couple of his lectures where my most vivid memory is how he terrorized unwary or unprepared questioners.

Then, one day—as I was preparing to leave the world of consulting researchers—better known as beltway bandits—to try my luck in the academic world, Joe made a point of asking my advice about a possible career change. Just as I was getting out, he was thinking of setting up his own contract research establishment. My inclination was to say "Don't!" However, since he seemed determined my advice was: Don't borrow money or sell stock; don't rent an office or hire a secretary. Run the business out of your house. Like all good (I mean successful) consultants, I told him what he already knew. He followed my advice, which made me feel like a genius. That must have been around 1978, though it could have been a year or two earlier.

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I am not sure how we made the transition from colleagues (of a sort) to good friends. It probably happened because we discovered that we both love a good argument. (Sorry: I meant to say discussion.) When my wife and I moved to Pittsburgh and I had to make occasional business trips to Washington, Joe offered his spare bedroom. Their propinquity to Connecticut Avenue, together with my cat allergy and the fact that he and Vary don't keep cats (whereas most of my other Washington friends and relatives do) tipped the balance. That and the Coates' family library, which is not quite as big as the Library of Congress but is a lot more interesting. Anyhow the Coates home became my home away from home a number of times, and every one of those overnight occasions was accompanied by a long and spirited three-way (or four-way if my wife was with me) discussion about some issue or other, usually involving an implication of emergent science or technology.

Because of his unique combination of breadth and depth, I have always considered Joe Coates the 'futurists's futurist'. He is not a TV personality. He doesn't write best-sellers or command five-figure lecture fees. (At least not every week.) He doesn't make dramatic pronouncements that the sky is falling, or that it is NOT falling (which pays better). He just knows a lot more about science and technology than most of us and he says sensible but not necessarily obvious things, most of which are right and some of which we haven't thought of, about what it all means for the rest of us. Thanks again, Joe.

Now, since this issue of the Journal is publishing some of Joe's reflections, I really ought to include something reflective of my own. It concerns the one example that sticks in my mind of a really (maybe) bad forecast on Joe's part. I can't recall exactly when or where it appeared but it was probably around 1995 or 1996. The forecast in question concerned the future of jobs and unemployment in the first decade of the present century. To summarize briefly, Joe projected very high and increasing unemployment, due (as I remember) to the impact of labor-saving technology in the service sector. The argument was, in essence, that mechanization in farming reduced agricultural employment to a tiny percentage of the workforce. But the excess agricultural laborers soon found work in manufacturing. Later, automation technology began reducing manufacturing employment. But the excess manufacturing workers found jobs in services.

However, when information technology (such as word processors and ATMs) reduces the need for labor in services, there would be no place for the excess workers to go, except to McJobs at the shopping mall, and the Temps agency. So, it would seem, unemployment must increase. Unemployment figures like 10%, or even more, seemed to be in the cards. I found this argument plausible enough to quote it in my own book *Turning Point*, published in 1998. So, I am not claiming superior insight.

If the cheerleaders had been right about the productivity increasing potential of IT, Joe's forecast would probably have been right also. However, I recall a remark made by Robert Solow in an interview in New York Review of Books in 1987 [1]. What he said, more or less, was "We see the computer age everywhere except in the productivity statistics." This remark became enshrined as the 'Solow paradox' and led directly to a major international conference in 1990 at the OECD, which generated five different theories, all of which probably had some merit, but none of which resolved the paradox [2].

Anyhow, it appears that both of us were wrong about the employment implications of IT (and the mainstream economists were right, although not because the Internet created such a lot of new jobs). What I now think has happened—and it was NOT one of the five theories discussed at the OECD conference—is described very well in a fascinating book by Edward Tenner, called "Why Things Bite Back" [3]. Tenner's point, as regards computers, is that the rapid increase in data processing speeds and memory capacity (Moore's Law) has not increased real productivity—except in a few well-documented cases—because the need for support functions and the drag on the productivity of other people have increased in tandem. In other words, IT has sharply increased the need for people to explain the software to other people and to fix the glitches which multiply faster than hamsters. The fact that most firms have failed to allow for this has actually reduced whatever potential for increased productivity faster and faster computers might have offered in a slower changing environment.

Both anecdotal and statistical evidence points to the fact that the highest paid specialists in our economy now spend less time doing what they are supposedly good at doing and trained for, and much more time doing what lower paid support staff used to do. I mean typing their own letters and reports, doing their own filing, entering data into spreadsheets and redoing work that was lost when the Windows system crashed because it couldn't (or wouldn't) cope with normal human errors.

Moreover, because software generations succeed each other with blinding speed, people who are forced to use personal computers have to spend more time than they would like, reading poorly written manuals and tracking down bugs that the software designers didn't catch (because they now depend on you and me to find the bugs.) In big organizations, it turns out that when help is needed, it is usually obtained from computer-loving colleagues 'down the hall' who happen to be familiar with the configuration and the software, rather than specialized service personnel. In fact, surveys have found that the this indirect cost outweighs, by a factor of two to three, the front end cost of the hardware and software, together with computer service support costs that actually appear on the budget.

As Tenner says "The relentless speed and efficiency promised by microcomputers and their networks, their computation capacity doubling every eighteen months, has a catch. The more powerful systems have become, the more human time it takes to maintain them, to develop the software, to resolve bugs and conflicts, to learn new versions, to fiddle with options... Early computer-minded historians were overjoyed at their new powers of quantitative analysis—until they realized that they would probably have to spend months or years entering data by hand before a machine could spend a few minutes processing and analyzing the data (pp. 266–267)."

In short, while the new capabilities have indeed created some truly productive new services—such as using the Internet for shopping and data retrieval—it is a fact not widely mentioned that by far the biggest single use of the Internet today is to provide easy access to pornography, and the second biggest use is for entertainment, especially sports news and games. Surveys have discovered that as much as 30% of the time of office workers nowadays is spent playing time-wasting games, like "Minesweeper" and "Solitaire" which were packaged with Microsoft's 'Windows' (not to mention other personal uses). In fact, it is arguable that the major new market that has emerged from the widespread availability of powerful microprocessors is computer games.

In summary, it appears that focusing on the cost of computers, rather than the cost of computing, has misled a lot of us, including Joe and me. We thought computers would replace a lot of people. In reality, they have probably reduced the productivity of some of the most productive people among us by wasting their (our) time.

Needless to say, I have no idea whether Joe will agree with my comments, temperate and objective as they are, but experience suggests that he will know something I don't and will have his own point of view. I look forward to hearing (or reading) it.

References

[1] R. Solow, We'd better watch out, N. Y. Rev. Books, (August 12).
[2] A. Lindbeck, Introduction, Technology and Productivity: The Challenge for Economic Policy, OECD, Paris, 1991.
[3] E. Tenner, Why Things Bite Back, Knopf, New York, 1996.

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Joe Coates—tribute to a master practitioner

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Whether to toast—or to roast—Joe Coates is the push and the pull of composing this recount of my professional and personal friendship with one of the great practitioners of the art and the science of futurism, futures studies, alternative futures or whatever voguish term that best describes it. This recount shares some personal insights and accomplishments contributed to the field of futures studies by this unique talent. On balance, I wish to pay my respects for the serious contributions Joe Coates has made and continues to make. In addition, I do not want to neglect acknowledging and paying homage to contributions across the domains of futurism by his colleague in these intellectual endeavors and partner in marriage, Vary Coates.

Summing it all up, I realize what a powerful impact Joe Coates has had on my own thinking about the future, many of those who will read this tribute, and the art of forecasting itself. In ways difficult to discern, Joe has made a difference in the very course of destiny affecting myriad problems and prospects of these times. Just as there are few grand masters in chess, so too are there few paragons of accomplishment and too few standouts in any profession or undertaking. But those that do stand above others deserve special recognition. *The Macmillan Encyclopedia of the Future* poll surveying leading futurists of all time ranked Joe Coates among the 100 most influential.

Over the past 40 years, I have been an active practitioner of futurism, I have witnessed a slow but steady disappearance of the vaunted few high-profile practitioners who made a difference. Many have eased into the shadows of yesterday. Every futurist stands of the shoulders of the best among us from whom we have learned so much—Buckminster Fuller, Herman Kahn, Isaac Asimov, John McHale, Bertrand deJouvenel and Robert Jungk, just to mention a few of the early proponents and practitioners of new ways for thinking about the future. Our work today builds upon and reflects earlier contributions in more ways than we shall ever realize. Where the previous "greats" left off, others have emerged. The long march of contribution continues. Today's retinue of the greats includes Alvin Toffler, Peter Drucker,

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John Naisbitt, Daniel Bell, Edward Cornish and so many more. Joe Coates figures prominently among contemporary practitioners whose work continues to shape the course of futures studies everywhere. I do not want to declare him a legend—yet—but he's close to it.

This special issue of *Technology Forecasting and Social Change* sizes up Joe's "footprint" on the course of futurism. Such recognition is the point and purpose of the observations recorded here in tribute to one of the profession's important practitioners. Observations, in my particular case, are based on a long and enduring friendship with one of the more important contributors to the emerging discipline we describe as futurism. Those who follow in the footsteps of Joe Coates will have some very large "shoes to fill"—size 14-B, to be precise.

Once I set my thoughts to contemplating who is Joe Coates and what, if anything, do those of us who have followed his work know about him, a great many conflicting views come to mind. Like many of you who may read this, we have all been on the inevitable receiving end of Coates' infamous style of searing acerbic put-downs. Smart or not so smart, renowned or unknown, most everybody who has come up against Joe Coates has, at one time or another (and usually most of the time), come up against the jabbing rapier and searing wit and witticism of his commentary.

In public forums and face-to-face conversations, many of them devolving into heated debate, I cannot recall Joe being at a loss for words—even if I knew for certain that he was wrong. I hasten to add that he may or may not actually have been wrong—sometimes the differences are merely a matter of a differing perspective. Whatever the circumstances may be, Joe always seems sure-footed and has an uncanny ability to recover and come up with a factually based scientific, or (when all else fails) pseudo-scientific (but plausible) explanation supporting his unswerving views. When taken to task for being supercritical, Joe's disarming response often is that he never graduated from "charm school." Not that I know many New Yorkers who ever did!

Joe and I have sparred with one another over intellectual inquiries into what the future holds and how to help manage it over most of our professional lives. Despite fleeting differences of opinion individuals may have encountered from time to time, the quest for knowledge and understanding, and the pursuit of finding and forecasting the best possible answers to the problems of today and, more importantly, tomorrow is always the end goal. Those of us interested in the relentless pursuit of difficult answers to contemporary matters, consider heated exchanges part and parcel of the "spirit of the dialogue."

Of course, I have seen hapless and sometimes dumbfounded victims of Joe's "thousand cuts" take umbrage. I have found myself in that predicament more than once, I can tell you. The cynical and piercing intellectual inquiry Joe engages in is not intended to inflict lasting pain. Instead, the purpose is to shock opponents or addle-minded to more carefully, more analytically and more thoughtfully consider their own comments and views. These barbs are hurled in the spirit of intellectual inquiry, and honing the substance of inquiry.

An important part of my futures research efforts involves discovering sound and serious thinkers and establishing "mentor file" for those individuals. Subsequently, when I come across something by, or about, that person it is posted to that file. I have several file cabinets full of such files. There is one file, however, that stands out among all of the others, not only for its sheer bulk, but for the consistent value of what the writer had to say. That thick file contains a great deal of what Joe Coates has written about over the past several decades. Commencing in 1991, Joe began a systematic and widespread periodic distribution of collected articles he (or his staff associates) published. I do not know the number of articles shared in this manner, but my guess is that it amounts to at least several hundred. It comes as no great surprise to me that the author most frequently cited over the past decade in Mike Marien's *Future Survey*, the World Future Society's authoritative newsletter covering important futures literature, is Joe Coates.

Joe's writing covers the waterfront of topics and issues. There probably is not a subject on which Joe could not comment with insight and prescience. He has served on editorial boards for a host of publications, including a current list of seven. Prominent among those positions is a long and valuable association as a member of the Editorial Board of Advisors for *Technology Forecasting and Social Change*. My own debt, for one, is beholden to Joe for so freely sharing his prescient insights and rigorous thinking about things to come.

I want to mention just a few published articles demonstrating how far in advance of problems plaguing the current issue landscape were addressed by Joe Coates many decades ago: *nonlethal weapons* ("Riot, Mob and Crowd Control: The Present State of Knowledge as Background to the Research, Development and Selection of Nonlethal Weapons." Institute for Defense Analysis, N-481, July 1967.); *DNA* ("The National Defense Implications of the in vitro Synthesis of DNA virus." Institute of Defense Analysis, N-533, January 1968.); *olfactory ID* ("Olfaction and Its Potential Applications in Personnel Detection." Institute for Defense Analysis, P-1;87, February 1965.); *electric power shortages* ("Social Impact Analysis Apropos of an Electricity Shortage." Electric Power Research Institute, 1977.); *Social Security shortfalls* ("Social Security in the Year 2000—How to Get There; and Where Will We Be When We Do?" *The Extended Family in Post-Industrial America*, Snyder, D. ed., AAAS Selected Symposium Series, Westview Press, 1979.). The list could go on, but you get the point. Being out in front—and nailing the issue on the head—is what the successful practice of futurism is all about. Early warnings provide time for capitalizing on opportunities and avoiding, minimizing or ameliorating problems.

Numerous books and a copious number of chapters in books have been published by Joe Coates, either in his own right or in collaboration with other colleagues. His recent book entitled, *2025: Scenarios of US and Global Society Reshaped by Science and Technology* (Oakhill Press) was ranked by *Future Survey* among the ten most important books published in the futures field over the past decade.

There's a page to be learned from this tremendous outpouring of published work which includes hundreds of articles appearing in a long laundry list of professional, intellectual and mass circulation publications. This outpouring represented far more than merely putting oneself forward and marketing promotion. Most important, is the intellectual generosity of sharing it. We expect such a copious output and sharing from academics and others in the nonprofit sector. But, for a entrepreneurial practitioner futurist to "give away" what they know, is quite a different thing. I confess that, when I was in business as a practicing consultant, I rarely gave anything away by openly publishing it. I played my findings close-to-the-vest. Usually, clients demanded explicit contractual guarantees against releasing findings because disclosures might "tip their hand" to competitors and they might compromise advantages made possible be foresight. In short, they paid dearly for the information and did not want to see its value diminished by widespread circulation. Many practitioners feel, as I did during those years, that what they have to offer to make their keep is the foresight and perspectives they provided. Giving it away by openly publishing findings elsewhere would compromise its unique value. I hope that others might catch the spirit of what Joe has done and continues to do—share the benefits of your insights and understanding as widely as possible. I learned this good lesson from Joe, and now avidly seek to publish everything I write.

Since I have sat down to peruse the stacks of articles Joe has written and the numerous books he has authored, I am more impressed than ever with all that he has accomplished. His style seems to be one of "been there, done that, what's next?" Well, he's into his "umpteenth" newest career. Among the latest "Joe Coates documents" in my mentor file, is one entitled, "The Reformatted Joe Coates!" Of course, he's up to date, as always. His new website is www.joosephcoates.com, and his e-mail address is joe@josephcoates.com. Just to fill out the profile: telephone is 202 363 7440 and fax is 202 363 4139. In that missive, Joe relates that he has retired from Coates and Jarratt, after 22 years, and is currently operating as Joseph F. Coates, Consulting Futurist. So, he's turned a new page by incorporating his own unique talents and making them accessible by modern electronic means. Joe had founded his futures consulting company, J.F. Coates in 1979, which became Coates and Jarratt in 1992. Coates and Jarratt continues on operating as one of the more successful futures consulting companies in the country.

Although our paths were to cross and become intertwined some years later, activities in which Joe took leadership roles mirrored my own interests and inclinations. Like ships that pass one another unknowingly in the deep of night, the paths both of us trod were eventually to lead to a career-long collaboration.

Years before I met Joe Coates, I worked for Congressman Al Bell who served on a subcommittee of the Science and Astronautics Committee of the US House of Representatives with Emilio Daddario. Both Congressmen were awed by the private sector contributions of NASA's lavish space program, and sought ways to convince constituents of the commercial spin-offs that promised to make life easier and better. From the political standpoint, extolling the commercial value of spin-offs underscored the wisdom of a Members' costly and unstinting support for the nation's ambitious space programs. Over time, these views gave rise to the need for assessing new technologies. This was, precisely, the expertise Joe Coates had been honing over the years, and the techniques that he is, perhaps, best known for. My assignment for Congressman Bell included researching and writing speeches extolling enormous and little-appreciated benefits that arose out of or were allied with costly programs to conquer outer space: optical masers, integrated circuits, weather satellites (1960); human orbit of earth, interplanetary microwave signaling, field-effect transistors, communications satellites (1961); computer storage disks, light-emitting diodes (1962); minicomputers, home video recorders, instamatic film cartridge camera, irradiated food, radio telescope (Arecibo, 1963); close-up moon photos, picturephones, geo-synchronous satellites, fully-automated factories, multiperson spaceflight (1964). Onslaught of this tide of technology and relative shortcomings of Congressional members to assess it all eventually led to introduction of a bill in 1967 to create an Office of Technology Assessment. Congressmen Daddario and Bell, among a raft of other Members, introduced the legislation to establish OTA. After leaving Congress, Representative Emilio Daddario's leadership was recognized by being appointed OTA director. Not until 1972 did Congress establish OTA to advise Congress on forward-looking consequences and impacts of Congressional policymaking (Public Law 92-484). All of this provided just the sort of opportunity that Joe Coates was looking for.

In no small way, politics played a vital role in establishing OTA. Congress, politically controlled by one party, realizing it could not count on unbiased executive department inputs provided by the opposition party. In response, Congress moved to establish a specialized research arm under its own purview that could provide viewpoints "unbiased" or more to its liking. Joe joined OTA as Assistant to the Director and head of the Exploratory Group where he made important contributions to Government public policy decision making between 1974 and 1979. Vary Coates, Joe's wife also served long and faithfully with OTA until its termination in 1995. Realizing the continuing importance of providing Congressional foresight and technological expertise in considering fast-paced scientific advances, Vary Coates has clung to the idea and hopes of resurrecting and continuing OTA-type functions. Joe's and Vary's commitments to this important aspect of Congressional foresight, sooner or later will prevail. It's just a matter of time until a successor foresight arm of Congress is established.

One of my treasured possessions is a US government check for US$1.00 which I had requested to establish my ambition to become a "dollar-a-year man." The check came, courtesy of Joe Coates, who had invited me to participate in a business advisory committee to the Office of Technology Assessment. Although I have served on numerous government commissions and committees, with this one exception, I have never accepted any reimbursement or compensation. Joe's only complaint was that it cost the government probably 35-times the face amount just to perform all the paperwork.

Prior to affiliation with OTA, Joe had made a name for himself on the Washington scene through his visionary work with the National Science Foundation, 1970–1974. The scholarly and expert inputs of work commissioned and guided by NSF plays a little noticed but important behind-the-scenes role in shaping government policies and programs. Joe's assignments at NSF involved interdisciplinary research, and he served as Program Manager, Office of Exploratory Research and Problem Assessment. Technology assessment was his forte, and his work in this area gained widespread recognition.

Prior to his work with NSF Joe had worked for the Institute of Defense Analyses, from 1962 to 1970. Like so many of today's senior futurists—Marvin Cetron, Joseph Martino, Herman Kahn, Leon Martel and myself among them—deep immersion in national defense planning honed serious interest in anticipatory policymaking.

Timing—being in the right place at the right time—can be crucial. In this regard, the timing of Joe Coates' edging entry into new foresight methods played an important role in attracting and holding his interest. The importance of the 1960s to futurism cannot be overemphasized. President Kennedy brought to the nation's capital a galaxy of future-oriented leaders that changed the nature of policymaking. The President's galvanizing pledge to put a man on the moon within the decade captured the spirit of the times. Defense Secretary

Robert McNamara brought with him rigorous forward planning techniques of systems management from his experiences at Ford Motor Company. Agriculture Secretary Orville Freeman zealously pursued long range thinking of food policies and programs. Glenn Seaborg, Chairman of the Atomic Energy Commission, assembled leading scientists and thinkers to ponder peaceful as well as military uses of nuclear energy's awesome potentials. All three of these prominent policymakers and trend setters became esteemed members of the World Future Society board of directors where their thinking and contributions helped to promote visionary thinking. Each of them—with exception of the late-Glenn Seaborg—continue to serve in that capacity.

Leadership exerted by these powerful figures on the national scene, created a milieu that fostered emulation by numerous other policymakers, intellectuals and futurists. Many of the leading futurists today—including Joe Coates, the focal point of this issue of *Technology Forecasting and Social Change*—were introduced to and persuaded to devote major time and attention to explicating future prospects.

Enduring friendships and career-long collaborations often begin with casual or chance encounters. Joe's pioneering contributions that helped to fashion fledgling forecasting activities brought me and so many others into this growing field. I probably would not have become acquainted with Joe Coates, save for a fledgling interest in futurism that blossomed during the 1960s. Working as research director for both of Governor Rockefeller's Presidential campaigns, I became acquainted with some futurists—Herman Kahn, Tony Wiener, Daniel Bell, John McHale, among them. Impressed by their marvelous ability to fathom the future, I began searching out things I could do to achieve a better understanding of just how one does go about divining the future.

As best I recollect, I first met Joe during the course of a half-hour interview on a radio show he hosted for several years. Joe broadcast this "future of..." series over 400 stations from WAMU, American University's radio station. I do not remember how he found me. It might have been a result of Ed Cornish's suggestion who I came to know during launching the World Future Society in 1966; or, through courses featuring visionary thinking that I began teaching in 1969 at American University's post-graduate business school. Joe's characteristic "take-charge" command of the topic, probing and poignant questioning, selection of important and timely topics gave me good reasons to want to get to know him much better. Many more opportunities were soon to come.

During the 1970s, Joe Coates was responsible for organizing NSF's Inter-Agency Committee on Future Studies on which I served as a representative of the business community. Although I had previously met Joe, this was my first close and continuous encounter with Joe's prowess. My respect for him continued to grow. Future-oriented representatives collaborated on this committee over a period of several years, and published collective and independent findings and forecasts.

Another link in our professional association was forged as a result of Joe's leadership roles in planning and conducting the First General Assembly of the World Future Society (1971). Observing Joe's role, not only in addressing important issues in his own remarks, but in marshalling a "galaxy of greats" with visionary portents of the future, was awe inspiring. Meeting so many other major futurists of the time, led me to undertake chairmanship of the

Second General Assembly (1975) where Joe Coates, once again, played a major role in organizing sessions, enlisting speakers and presenting his own views. From the "get go" Joe Coates has always played a major role in every facet of WFS activities. Sessions Joe conducts at WFS assemblies are among the biggest draws at those meetings.

Joe's leadership in other organizations interested in long-range planning and the future are legion. Scores and scores of organizations have benefited from Joe's unflagging efforts to advance interest and confidence in the various fields of so-called futures studies. When the Society faces difficult problems or contemplates novel undertakings, Joe Coates invariably is one of the seasoned veterans who contributes assistance in finding answers. I cannot recall a time when Joe has failed to respond or say "no" when asked to do something that in some way contributes to futures studies. Joe has always willingly contributed time and thought to every major WFS project he's been asked to help out on. Leadership roles, ranging from president to boards of directors or advisory boards spans nearly one full page of his impressive resume.

Before his stint with national defense and policy planning, Joe spent a number of years practicing his profession—chemistry. After obtaining a BS degree in chemistry from the Polytechnic Institute of Brooklyn in 1951, he went on to secure an MS degree in organic chemistry from Pennsylvania State University in 1953. I'm not about to say that Joe Coates should be compared to the alchemists of medieval days who essentially were practicing futurists of another era. But, here goes. I find it interesting to note that Joe next decided to hone his skills in a different academic discipline. Between 1954 and 1957, he pursued graduate study in philosophy at the University of Pennsylvania. Chemistry and philosophy provide—in my humble estimation—about as close a credentialing in "alchemy" as one might conceive. Not to say that the study of the future is a sorcerer-like skill. But if any practicing futurist today comes closer than Joe in fitting the job description that's been around for something short of 1000 years, I cannot think of who it might be. Joe was awarded an honorary doctorate by Claremont Graduate School in 1985.

Next, Joe applied his newly won academic accomplishments as a teaching assistant in philosophy and chemistry at the Pennsylvania State University from 1951 to 1953. Always the teacher, always interested in passing along skills about divining the future, Joe—to this very day—continues to ply those skills. He has schooled untold thousands of individuals in forecasting skills. I have had the pleasure and the privilege of being a student of Joe's by attending the first six-part course he taught at the World Future Society headquarters during the early 1970s. Years later, I teemed up with Joe to teach courses at WFS assemblies and at the Smithsonian Institution, among other forums. Joe is skilled at inculcating knowledge about the techniques and methodologies of forecasting that have served him so very well over the many years he has practiced this art form.

Leaving the university life behind him, Joe commenced his professional career practicing his skills as a research chemist. Initially, he worked for Atlantic Refining Company as a research chemist focused on extracting myriad marvels from petroleum from 1953 to 1960. Subsequently, he worked as chief research chemist with Onyx Chemical involving specialty chemicals, surfactants and biologically active agents from 1960 to 1962. During the course of these stints, he amassed 19 patents involving surfactants, germicides and bacteriostatic agents.

Joe's 1953 thesis at Pennsylvania State University, "Studies in Hexamethylacentone," calls forth an anecdote. Over the years, I have hosted formal dinner parties at my home. Invitees typically included a Member of Congress, a Washington lobbyist, a newspaper columnist or Washington bureau chief and an intellectual guest of honor. One such dinner, when Joe was the intellectual guest, we enjoyed a spirited discussion. But, what I recall most vividly was an impromptu discourse Joe launched into. The dinner was accompanied by three courses of wine. When the desert course of wine was served, Joe commenced to detect and describe the complex of ketones and esoteric chemical constituents that made up the exquisitely sweet and delicate flavor notes of a *Trockenbeerenauslee* (late gathered—third picking). We all got an interesting scientific grasp on the subject. Sometime later, I invited Joe to a wine lecture/tasting banquet at a downtown club. At one of these sessions, Joe and I—deciding that we really liked a couple of the selections—decided to stay on afterwards to make sure the leftovers were properly disposed of. We gathered together nearly 100 partially filled bottles of vintage wines on a huge roundtable, and joined by a few other die-hards, did our very best into the wee hours of the morning to deal with the task set before us. To this day, I am still not certain exactly how I arrived back home in Potomac, MD. I do not recall asking Joe how he managed. Some people have minds that are a mile wide and a fraction of an inch deep. Not so, Joe. He never speaks about his knowledge of wines, but I have the feeling he knows far more about them than I do after all the books I have read. And, I am dead certain that a list of such surprises is long.

Joe Coates, always among those in the forefront of new and interesting developments in long range planning, has embarked on audacious new efforts to probe the future on the very long-range scale—looking 1000 years into the future. Over the past 3 years, Joe has been involved in efforts undertaken by Walter Kistler and Robert Citron at the Foundation for the Future. Joe's organizational responsibilities include very active involvement in the Organizing Committee and the Board of Advisors of the Foundation for the Future. Along with Joe, I have had the pleasure of membership in these activities. From that vantage, I can attest to Joe's typical outspoken, provocative and constructive contributions to nurturing this new field of endeavor. Seeking to devise techniques and understanding probing so distant a future will require many years of input and Joe's contributions, judging from performance so far, are certain to be extraordinarily valuable to this new dimension of visionary thinking.

So, there's the long and the short of what one colleague recalls and remembers about the many and myriad contributions of one of futurism's most accomplished practitioners. Thanks Joe Coates for everything. I am still looking for much more in the coming years.

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Raising the bar of professionalism in futures studies

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Abstract

This article gives a behind-the-scenes look at how Joe Coates has been fulfilling an agent provocateur role for futures studies in the continuing high quality of his work and his watchdog-like role over the output of the field as a whole. © 2002 Elsevier Science Inc. All rights reserved.

To my mind the great contribution of Joe Coates to futures studies is in bringing a provocative and tough-minded approach to a field often characterized by soft thinking. He has helped raise the bar of professionalism in the high quality of his work and his watchdog-like role in analyzing and critiquing the output of the field.

I have been a student admirer, intern, staffer, business partner, and client of Joe's. From these multiple perspectives, I hope to capture some of the man behind the work, as a mini-case study to current and prospective futurists about how one of the giants of the field goes about his craft. I was introduced to Joe's work as a graduate student in the University of Houston-Clear Lake Studies of the Future Program. I found his writing to be clear and straightforward, and I was impressed by its practical application. When it came to think about getting a job, it seemed to me that his ideas and his firm were the best place to consider a career. So I interned with Joe over a summer. I recall the "warnings" I received from several colleagues about this plan. They pretty much said that he's very tough, but you'll learn a lot. And they emphasized tough. This turned out to be an accurate and useful advice.

Those of us who have interacted with Joe know that he can be blunt in his critiques. He is a sworn enemy of what he feels is weak or substandard thinking. He spares on one or nothing in his assaults. The intimidation factor was perhaps accentuated by his six-foot-seven frame and deep voice. But those of us who got to know him saw that underneath this tough exterior was a man who was motivated by the love of his work and the field. His belief in the importance and usefulness of looking to the future led him into the role of provocateur and

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something of an enforcer as a means of protecting and developing the field. Thus, he was the enemy of soft and lazy thinking. And he constantly challenged colleagues to improve their work. I would wager that any readers presenting at a conference where Joe was going to be there would take some extra care in their presentation, knowing they were going to be in for an extra challenge. I found it amusing that in writing this piece, I often thought about how Joe would respond to a particular point. His voice remains present in my work today, as a reminder to sharpen it up.

Still, the challenging role was often quite a shock for the uninitiated, including clients. For Joe, sloppy thinking is sloppy thinking, and no one is exempt. I'm sure that over the years some business was lost as a result. At the same time, I know that many clients appreciated that they were getting the straight story. Many complained how typical consultants would often tell them what they wanted to hear.

With Joe, clients knew they were getting the unvarnished truth. While he is well known for challenging others, it must be noted that he sets the bar very high for himself and his team. He was firmly committed to lending credibility to futures consulting. His and our work had to be derived from a reproducible methodology and data.[1] Many times I heard reporters ask him what separated the good futurists from the charlatans, and the answer was always that the good futurists used a method that they would openly share and could be examined by clients. There was no mystery. No reliance on the unexplained. It was spelled out how we got from A to B. All of our work to clients included an explanation of how we came up with it and the sources we used. We had a project in which a client asked us for 16 one-page scenarios, period. They had liked our previous work, but found that their internal constituency preferred the summary and did not need the binder full of supporting information we provided. So the job spec was just for these 16 one-pagers. We did deliver the one-pagers. But we could not help ourselves and insisted they take the 400+ pages of supporting documentation we generated. We also routinely included a feature called "digging deeper and keeping up" that pointed clients to additional sources.

Joe is very open about how he does his work. As described above, as consultants we were very open about how we did our work. He published hundreds of articles and gave hundreds of public talks that described how he did it. I once asked if he was not worried about being "ripped off." He laughed and responded that those who would try to do it wouldn't know how. The value was really in the people behind the technique rather than the technique itself. This was a gift for the field. I have adopted the same approach in my work, arguing that sharing leads to the development of methodology, and that our challenge is to keep improving in order to stay head of the imitators.

Another manifestation of this openness was his rule of giving away one day's worth of consulting per week. It was always my sense that we were much more a think tank than a consulting company—if you'll accept the distinction that a think tank is concerned with spreading the message first and a consulting company money first. Joe is fond of saying that, "money should never get in the way of doing a good thing." We were often creative in

[1] See FRQ piece that is an excellent summary of the generic approach developed by Coates.

finding ways around budget constraints. I remember one project for a consumer electronics company in which we were paid for with the company's products—I still have that VCR. There were ways that we could have made more money, but that's not what it was about. This was a firm that was founded first and foremost on doing useful and interesting work. Each year, we would spend some time deciding what we wanted to do in the upcoming year. Staffers could propose project ideas. While there was certainly an element of practicality in what we proposed—we were aware that somebody would have to pay for the project—we proposed things we wanted to work on. This created a passion for the work that I believe was a key element of our success.

The work had to be useful. The key overriding principle comes from his philosophy of pragmatism. While we lived and breathed in the realm of ideas when in the office, there had to be a translation into very concrete recommendations and action steps, or the work would not make it out the front door.

One of the most stinging criticisms we could receive was that we were being either "academics" or "ideologues." Both monikers arose from a perception that our work was being self-indulgent and not serving the needs of the client. For my part, I was more often guilty of being an ideologue, but I am grateful today that I have absorbed the lesson of understanding where my biases lie, and being very careful or at the least, open about them in my current work. This emphasis on being aware of our assumptions and delivering practical recommendations was another virtue of our work that clients consistently expressed gratitude for.

While Joe is very opinionated and has a strong personality, he always sought feedback and listened. He made the final decision, but always gives an opportunity to make your case, and most times would be influenced by strong opposition to his views. For example, he once asked a colleague for advice about whether to keep on an intern. He had his doubts and the economy wasn't great. We argued strongly that the person was worth the investment and simply needed time to develop. Joe accepted our advice and that former intern today is one of the rising stars of the futures field.

I think I was the first to dub Coates & Jarratt, as "boot camp for futurists." Many times aspiring interns or futurists would ask me about working for Joe and the team, and I felt this phrase summed it up nicely. Not everyone can make it through boot camp, but if could, you became a strong soldier. Probably the key test was the first group review of your work. The beauty of the job—and Joe often told us would be the best job we would ever have—is that once the group outline a particular project or topic, you as the lead author had complete freedom to prepare the initial draft. But you had to pass group muster. And I'll confess that experience could be excruciating. Most of us think we do good work, and are smart people, and to have our work shredded can be very humbling, to say the least. But if you could survive this, it did eventually make you stronger. Ultimately, I think Joe can be very proud of the talent that he and the firm has helped shape for the rest of the field.

I often tried to get Joe to reveal his secrets of how he became a leader in the field, as I probed him for advice on my own future. Early on in my tenure at C&J, I thought there must be some kind of secret recipe to Joe's success. He explained that he simply set a goal to be the world's best futurist and then went after it. He suggested I do the same, and assured me that this was achievable. While I was initially frustrated by what I perceived as a lack of help, I came to see the wisdom behind this advice over time. It was clear it was less about magic and more about hard work. I saw Joe work six full days a week. And I'm sure that his work was never far from his mind on the seventh day. And while on the job, he was, as mentioned, continually challenging himself to improve his approach.

For those readers aspiring to be future provocateurs, let me suggest that such a role can have its price. I suspect it is occasionally lonely to be the one raising the challenge and taking on the field. But there is no doubt in my mind that such a role is needed in our community, and we all owe a debt of thanks to Joe for filling it so admirable for so many years.

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Joseph F. Coates...or the quiet strength of experience A personal reminiscence

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The circle of futurists is small and most members know all the others by their publications. I have been fortunate enough to meet some of the most famous futurists including Bertrand de Jouvenel, Philippe de Seynes, Edward Cornish, Olaf Helmer and, from the world of strategy, Igor Ansoff. Among those of my own generation, I have had the pleasure of knowing Jerome Glenn, Clem Bezold, Eléonora Masini and Peter Schwartz. Indeed, it is by working with the top futurists in the field that you can grow and also challenge yourself, as I have been able to do over the past 25 years with Hugues de Jouvenel and Jacques Lesourne in France.

I also was fortunate in having the incredible opportunity of working twice with Joseph F. Coates. I have only one regret—that it did not happen sooner! The fault is all mine for Joe had expressed an interest in my work when he prefaced my book "From Anticipation to Action" (Unesco, 1994) and again "Creating Futures" (Economica, 2001). I should have had my eyes and ears open earlier, as there is much to learn from this man, whom I consider the greatest living futurist.

In December 2000, while listening to Joseph Coates speak about future technologies to an audience of hundreds here in Paris, I realized how much better he was than the other speakers—including myself. He did not need slide or power point presentations to captivate his listeners. He simply looked up from his notes occasionally to emphasize a key idea. The essential came from his thoughts expressed in resoundingly clear sentences made up of simple words.

What struck me while listening to Joe Coates was his youthful stare and powerful message. Everything appeared clear and everyone felt more intelligent. Only the truly great possess that quiet strength and can make complexity understandable with simple words.

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In May 2000, I had the honour of joining Joe on the podium during a two-day seminar in Scotland. We addressed some 60 executives from Montgomery Watson, a California-based firm active around the world, especially in Asia.

I was impressed by how dynamic Joe was in leading such a large seminar alone at age 72. I helped him just so that I could feel useful and also so that I could experience the event from the inside. One thing is remarkable: Joe uses no visual aids. His foresight workshops resemble those we hold in France in that silent individual work is included. However, his workshops are far simpler and use more group work in plenary sessions. Overall, the results are perhaps less systematic and participants would have to dig deeper later, but the way in which Joe Coates led that group was incredibly efficient. In fact, the participants eagerly organized themselves in groups!

Review of trends workshop.

Plenary session task

1. Working on your own, list one or two variables that have affected your sector over the past 20 years.
2. Vote as a group to decide on the three most influential variables from the past.

Subgroup exercises

1. Take one or two minutes alone and silently list the most important factors for the future of your business activity.
2. Using consensus, list four to five factors as a group.

Plenary session

(1) Collate all the lists of four to five factors from each group.

(2) Vote as a group on all of these factors using applause as a measurement so that only 10 or 20 key variables remain. These are considered the most important and the ones that require foresight the most, e.g., political situation, labour skills, legislation, economic environment, IT, competition, workforce and population.

Parallel workshops

1. Choose a strategic vision, e.g., establishment in China, doubling size and multicultural staff.
2. Build several scenarios of visions compatible with this strategic vision with regard to previous key variables.
3. Vote on four or five of the 'standard' visions from the vision scenarios.

"Scenario" workshop

Build the optimal scenario for this strategic vision.

Debriefing session.

"Action" workshop.
Subgroup exercises

1. Point the consequences for the company.
2. Identify the action to be taken by the company.

At this point, in France, we use systematic individual and group voting procedures. Joe Coates uses the simpler method of applause instead. Where we generate grids to build scenarios through morphological analysis, Joe sticks to a few scenarios of strategic visions based on key variables.

Later, I asked Joe about using something like morphological analysis because I know he is well acquainted with such methods. In fact, he was one of the firsts to use them in the past. He replied that something like morphological analysis is too difficult for a large group that has to think together for a short time. In the end, I realize that the French School's approach may be more rigorous but it is certainly harder to manage than Coates'. With his incredible talent as a facilitator, he makes his approach effective. Participants certainly interacted and shared intense, useful moments of group reflection. In addition, after all, is that not the essence of the whole exercise?

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Unconventional wisdom for the future

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Like a blank page, the future remains to be written. Any form of prediction rings hollow because the future is wide open. It is up to each of us to take charge of the future; in other words, to plan together for a desirable future. In the words of Louis Pasteur, 'determinism cannot withstand determination and chance favours only those who are well prepared.'

Nevertheless, the ringing in of the third millenium generated a flood of proclamations similar to the doomsday warnings of the year 1000. Thinking about the future has always been an opportunity to let loose and give free reign to dreams or nightmares. It usually boils down to enchanting fairytales or horrifying ghost stories about supposedly revolutionary, unprecedented technological advances.

1. The overestimation of technological change

Of course what is technologically possible is not necessarily profitable or socially desirable (beware potential 'Concorde airplanes' in cable networks). Witness the case of the home office or telecommuting. It is unlikely that working from your home will develop to the point where most office jobs disappear. Several factors fly in the face of this maximalist hypothesis. First, the actual layout of suburban housing (small lots, ill-adapted rooms, unstimulating environment) makes the average household an unrealistic setting for entire days of work and family living. Second, and perhaps more important, there is a very human need to communicate and enjoy social ties which cannot be created elsewhere. In fact, these ties are less and less satisfied elsewhere.

We also tend to overestimate the speed at which technological changes actually occur. Naively or egotistically, we tend to think that ours is an era of unprecedented change, after

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which nothing of similar importance will ever take place. Carried away by their enthusiasm, some commentators go so far as to say that it is the beginning of the end of the world, a perfect world or even the end of history! This bias is perfectly normal because each generation believes that it lives in exceptional times. In a sense, each generation is truly exceptional because it is the only one to live through those times!

However, we should stop trying to scare or impress ourselves by announcing that two-thirds of the products of tomorrow do not exist now or that tomorrow's skills are unknowable today! In many respects, the Europe of the year 2002 will resemble that of 1999. For example, children will continue sitting in classrooms with blackboards and chalk despite the portable computers in their schoolbags.

2. Internet: a computerized dumpster!

The high-tech mirage frequently floats to the foreground. First, there was the fifth generation of computers, and now the Internet. Like Bruno Lussato, we are tempted to see the Internet as a computerized dumpster or rubbish bin. Of course, a dumpster may contain hidden treasures—everything and anything—but that is no reason to spending time picking through garbage.

That said, a garbage pail is useful in the home, and e-mail represents fantastic progress. Indeed, some people boast that they spend hours everyday communicating with the rest of the world on the net. However, often these cyberhermits never even speak to their next-door neighbor. The massive popularity of surfing the web or navigating the net reveals tremendous solitude and the need for human contact. The main advantage of cybercafes is that they let the hackers and cyberhermits talk to one another and not only to a screen. Of course, many people achieve the same effect by taking their dog for a walk!

This is truly the great paradox of modern society: information technology makes everyone closer, connected to the entire world, but with no one nearby for a talk. As a result the wealthy are willing to pay a psychoanalyst simply to listen to them! In terms of human contact, telecommuting, or the home office, does not spell progress and will, therefore, remain marginal.

Tomorrow's generation will be just as active as today's. People will look to their work as a form of association or belonging. Their office may be a workplace but it is also a place for mutual recognition and social ties. Without social interaction, life loses its meaning and becomes a lonely place where cyberhermits stay online so long that they crave human contact.

Although we overestimate change, we underestimate inertia; in other words, that which does not change or changes very slowly. In reality, the world changes but the problems remain the same because they stem from human nature. Human nature appears to be the great invariable of history. The same drive for power or money, the same loves or hatreds drove the ancients as do the moderns. Politicians know that the proportion of traitors in their midst has not decreased since the time of Judas.

We have to study and know human nature in order to understand what is happening. We need a memory of the past to shed light upon the future. A line in Visconte's film *The Leopard* tells us that "everything has to change for everything to begin again." The world may change, but people maintain an eery resemblance in their behavior. Placed in a comparable situation, they react in almost the same manner and, as a result, their behavior may be predicted.

3. The model of the Catholic Church

For further proof, we can always turn to one organizational model that has stood the test of time, the Catholic Church. They started with 12 and have kept going for 2000 years! No multinational can boast a track record like that!

It is worth noting that the Church's organization is actually quite modern. There are only three hierarchical levels: Pope, bishop and priest. We also see the strict application of the famous subsidiarity principle promoted by the European Commission in Brussels. There is broad-based activity ranging from orders that uphold a vow of silence to orders that walk among the poor of Calcutta. The Church has an international marketplace with some slumping segments like Europe and other expanding segments like Latin America. Nevertheless, the longevity of the Catholic Church may be explained by strong individual commitment to a collective project carried on by highly structured communities.

No matter what, the human factor lies at the heart of any difference. By looking for scapegoats in technology or globalization, we can not shirk our responsibilities. For many companies, territories or individuals experiencing difficulties, the problem stems from internal weaknesses or insufficiencies not from some external force.

The future of an individual or an organization depends largely on its internal strengths and weaknesses. Modern management has rediscovered the importance of ancient Greek philosophy, notably Socrates' advice: "Know thyself." Before asking where we want to go, what may happen and what we can do, we need to know who we are and know it well. As the 18th century French writer Vauven argues put it: "knowing our strengths increases them; knowing our weaknesses reduces them." The key to success or the cause of failure comes first and foremost from within.

In fact, there can be no technical or economic solution to problems of a different nature. Rather, like the Band-Aid approach, this type of problem-solving resembles a desperate parent giving candy to a child seeking affection. Tomorrow's issues are in fact related to social breakdowns or faultlines and the spiritual vacuum of a society in which economics does not give life meaning.

4. Growth and the search for meaning

In many respects, quantity has led to a decrease in quality. The example of human relations stands out. Although we have more means of communication, loneliness and alienation plague the Western world. Growth that is richer in quality could also mean greater well-being overall. After all, who ever said that consuming more and more material goods would make anyone happier?

Growth is rather like drinking wine. Rather than drink more table wine, progress would be drinking the same amount, or even less wine, but of a finer vintage. A civic-minded enterprise, 'the good corporate citizen,' cannot be content with creating material wealth. The corporation must also contribute to people's personal development. There can be no 'excellence' in a corporation where there is no environment of excellence. Salaried workers need a quality environment, especially in terms of architecture, to be productive. They need a sense of satisfaction. In our urban world, people have to develop personally at work. Work, happiness and human growth are part of the same bigger picture.

People seek out social ties and some meaning or direction in their lives. The despair that many express today is real in that they suffer from loneliness. This solitude is especially painful for the unemployed who remain outside the social network that a job provides.

Tomorrow's big market is actually loneliness and meeting the need for human contact. In that case, hooking everyone up to the information highway is obviously a dead-end solution!

We need to reverse the usual order and start over with an individual trying to give his/her life meaning. I once overheard a father tell his son: "If you do not live the way you think, you will think the way you live." It is really up to us to decide whether we want Roman decadence in the form of bread and circuses (substitute TV for lions) or the Athens of citizens (substitute new technology for slaves).

The best of times or the worst of times lie before us. However, the dead should no longer rule the living and we should not transmit to future generations a negative heritage. We must always remember that we did not inherit the earth from our ancestors but rather borrowed it from our descendants. Historian Pierre Chaunu has conclusively shown how the population of the Roman Empire (Second Century AD summit to its Fall in the Fifth Century) fell by 50% from 60 to 30 million. The demographic decline thus preceded the economic and political decline.

All economists recognize the link between growth and job creation. Those who study the levers needed to stimulate growth usually evoke a lack of either demand or innovation. Rare are those who make the connection between economic growth, job creation and demographics. Economists 'refuse to see' as Alfred Sauvy once said and thus do not try to confirm it.

Yet, postwar prosperity and the babyboom went hand in hand. Yes, economic growth in the United States may stem from innovation, but healthy demographics have certainly played a major part, too. In the past 20 years, the fertility rate in the USA has been two children per woman versus 1.5 children in Europe. The American population, swelled by major influxes of immigrants, continues to grow while the European population stagnates.

In 2025, the Europe of Fifteen will have as many inhabitants as in 1999 (380 million). It will be surpassed by the population of the southern and eastern shores of the Mediterranean, whose numbers will have more than doubled. Among the developed countries, Russia, Former Soviet Bloc countries and Japan will suffer demographic decreases greater than those in Europe. Europe and Japan resemble orchards in which the trees have reached maturity after 40 years of bountiful harvests. Unfortunately, no one thought to replant.

The demographic implosion in Europe will be spectacular. In 1975, the French population included 1.7 million more youths under the age of 20 than it does today. Over the past 20 years, the fertility rate in Northern Italy and Catalonia has plummeted to less than one child per woman (2.1 per woman would be needed to reproduce the generation)!

Yet, compelling correlations reveal that the industrialized countries which have created the most jobs and have reduced unemployment the most are also the countries in which the population has increased the most. How can anyone believe that everything will be all right after the year 2000 because of the decrease in Europe's active population? On the contrary, the demographic implosion and the combined granny-boom and baby bust will heighten social and economic tensions. Among the many examples that spring to mind: Who will finance old age benefits when the age pyramid flips like a toy top? How can we integrate future immigrants when there are fewer and fewer children actually born in the county in the schools?

Imagine what ecologists would say if the fertility rate of whales had dropped by half to end up at the very threshold for population maintenance. The hue and cry would deafen the media and international opinion would certainly be affected. Yet, this is exactly what is happening to the Catalans and Lombards whose cultural variety is worth conserving. Overall the human race is not threatened, but cultural diversity which contributes to the richness of our human heritage is indeed in danger.

Given the stakes, the principle of precaution, often used in ecological debates, should also be applied to demographics. The link between demography and economic growth should be treated in the same manner as other human activities like global warming. There should be research into the hypotheses of causality. In the meantime, conservation measures that favor the birthrate should be taken. Protecting our planetary heritage is admirable but we should not forget the heirs. However who is looking at the human capital, or the demographics, in this manner? Almost no one. It sounds politically incorrect in today's world to defend children and whales in the same breath.

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Technological Forecasting and Social Change

A forecaster's forecaster

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Any salute to our teacher, mentor, model, and friend—Joseph F. Coates, a forecaster's forecaster and a public intellectual of distinction—would not be complete without a field report on his unique standing with several hundred futurists who annually crowd into a hotel meeting room to learn from him.

Among serious futurists, the name—Joe Coates—earns instant recognition and respect. He draws standing-room-only crowds when he shares ideas as a solo speaker—for session after session throughout a single day—at the annual meetings of the World Future Society (WFS). Alone, and relaxed at the front of the room, he will divide his sequential sessions by the decades ahead, or by subject matter, or by some other rubric that would ordinarily require a panel of specialists.

People marvel at Joe's energy, his patience, his breadth of material, and his empowering mix of personal audacity and genuine interest in what others are thinking. Obviously enjoying himself when questions are specially good, Joe effortlessly crafts answers audience members rush to capture in their notes, even as tape cassettes of his words later outsell all others.

Year after year, these engrossing seminars enable Joe to elucidate the most complex and arcane matters, the better to raise the bar where forecasting is concerned. A voracious learner, he models a rare kind of intellectual integrity. A masterful raconteur, his presentations are graced by a far too rare dash of humor.

Arguably, no other speaker at a WFS event is held in such high regard, so renowned is Joe's grasp of creative possibilities (and awesome perils), and so intriguing is his daring and imaginative material. He always reserves considerable time for questions, sometimes of a doubting or even sharp and challenging nature. Short with the rare silly query, and curt with even rarer boorish ones, he approaches all others with informed authority and a unique range of current knowledge. Listeners get a better-than-ever grasp of issues of deep and far-reaching importance.

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Joe's presentations for the WFS regularly explore the implications of current policy options and creatively weigh alternative futures. Too responsible to slide into point forecasts, Joe helps us renew our sounder commitment instead to explicating unexamined assumptions about the future, and exploring the major alternative futures we can and must help chose among.

No other forecaster I know of brings to the WFS gatherings Joe's wealth of knowledge (based, in part, on decades of consulting fieldwork), his independence of thought, and his craft in communications.

In all, Joe Coates reminds me very positively of a character J.D. Salinger may have had in mind when he entitled one of his nine short stories, "Raise High the Roof Beams, Carpenter." In that classic tale, we learn from a Norse legend that in ancient times, a messenger was sent out ahead to advise an expectant host to lift up his home's ceiling for a traveler headed that way—so "tall" in distinction and ability was the oncoming guest. Coates stand out in just this way.

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Technological Forecasting and Social Change

Computer power and union prospects: CyberUnions or faux unions?

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Abstract

Innovations in the use of computer power may offer the American labor movement an opportunity to reverse a 50-year decline. Progressive unions and locals have been experimenting with computer technology, and a "CyberGain" model today commands respect in and outside of Labor. While indispensable, the model appears insufficient. A case is made for adopting a radically new approach, a CyberUnion model, whose four components (futuristics, innovations, services and traditions) appear relevant to technological modernization efforts by labor organizations and many other types of bureaucracies. © 2002 Published by Elsevier Science Inc.

Organized Labor, down now to only 13% of the American work force from 35% in the 1950s, confronts at least three major threats to its existence: The first, its loss of jobs sent overseas, is obvious [1]. The second, a recent rise in well-being of certain members, poses an ironic risk. And the third, confusion about using computer power, while a threat least well recognized in and outside of Labor, is arguably the most critical hazard of all [2].

Threat #1: Outsourcing. As has been obvious for at least the last two decades, Organized Labor is seriously threatened by a main strength of global businesses. Companies with branches everywhere and "deep pockets" are shifting more and more unionized jobs overseas to low-paying, little-regulated labor markets in Central America, Eastern Europe, Mainland China and Southeast Asia. In 2001 alone, manufacturing, a heavily unionized sector (15% vs. 9% in the private sector), lost 1,300,000 jobs, with no end in sight [3]. From 1984 to 1997, in the eight industries with the greatest job loss (autos, steel, etc.), about 80% of the jobs lost belonged to unionized workers [4].

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Labor leaders condemn the competition among global firms to use the cheapest possible work force as a "race to the bottom." Unions try to bargain for protections against job transfers. They seek plant-closing laws. They lobby to have labor standards included in trade agreements. And they turn out thousands to protest multinational trade agreements they blame for allowing offshore job losses. However, as Teamster Union economist Robert E. Lucore notes:

> ...to date, these efforts have not stemmed the tide toward decreasing union density... It is virtually impossible for a union to survive, or even gain a toehold in an industry where cutthroat competition prevails [5].

Threat #2: "Working class tories." Ironically, recent wage gains by many workers may undermine Labor's staying power. While little noticed by the media or the popular culture, large numbers of upwardly mobile workers did very well in the boom decade of the 1990s. Business Week "calculates that workers received 99% of the gains from faster productivity— growth in the 1990s at nonfinancial corporations... [which] helps explain why consumer spending and the housing market stayed strong during the 2001 recession... All told, real wages for the average private-sector worker rose by about 14% in the 1990s business cycle..." [6].

Many well-off workers may think unionization unnecessary, at least as long as they continue to "feel financially comfortable (a social–psychological effect known since the 1960s as the 'embourgeoisification of the proletariat') [7]. This can take the form of workers—newly indifferent to Labor—employing what is known to academics as the Exit Strategy (quitting one job to take a better one) in preference to choosing the Voice Strategy (sticking with the union and fighting for gains) [8]. Especially in a culture like that of America, where class membership is lightly and unevenly held, where it is somehow odd to seeing oneself as a beneficiary of collective representation, unions have long been buffeted by this sort of conscious drift away from collective bonds toward "Me first" individualism.

Threat #3: Computer power puzzle. Threats #1 and 2 leave Labor no choice: It must attract new members less vulnerable to having their jobs sent offshore. And it must appeal to upwardly mobile workers, both those already within and those others still only potential members. Labor must organize outside its traditional strongholds, and it find new sorts of "glue" and fresh appeals. All of which explains threat #3: Unless Labor soon figures out how to use computer power to alleviate threats #1 and 2, it will fade into insignificance.

Response #1: Reaching members online. To help replace members whose jobs have gone offshore, unions are focusing on workers whose jobs are far less vulnerable. Many work in the public sector, which in 2001 added 485,000 posts, and in Health Care, with 300,000 new employees [9]. Both sectors boast a dedicated and proud work force with comparatively high educational attainment, specialized skills and a very attenuated identify with the traditional blue-collar working class and its labor unions: As such, these prospective members pose a difficult cultural challenge to union organizers.

Accordingly, creative efforts are underway making fresh use of computer power. Reaching out, for example, to such new types as doctors in HMOs and graduate assistants on campus— unions are using the Internet to establish virtual locals. Designed as incubators for fullfledged unionism down the road, these shadowy "locals" collaborate via union-operated list serves with one another around the country. They trade field-proven advice and lend precious morale support. Patiently proving the case for formal unionization, they promote a new cultural form of "electronic" solidarity—and wait for the right moment to push for formal representation [10].

To hold on to members lifted in the 1990s into the ranks of the seeming well-off, many unions are addressing their known interest in securing further schooling and new educational degrees. Unions are busy exploring how to use the Internet to offer Distance Learning programs in cooperation with allied colleges and universities, e.g., the National Labor College of the AFL-CIO George Meany Center for Labor Studies is pioneering this innovation.

Considerable attention is also being paid to a highly regarded effort to unionize Microsoft workers in Seattle and elsewhere: This educationally focused campaign offers prospective members cut-rate, high-quality computer training courses at a union Training Center, "fringe benefit" that has proven to have great appeal. In San Jose, a comparable Labor-run program helps "temps" upgrade their skills, the better to possibly enjoy their support some day later when a unionization campaign is in play.

A second track uses computer power to help "organizing the organized." It emphasizes creating strong social bonds among former strangers. To this end, locals are busy their website as a 24/7 electronic "newspapers," rich in very current coverage of the activities of their members. Photos of participants in a union picnic or a local meeting can appear within a few hours of the event (or sooner!). Very personal and very current news of births, graduations, retirements, etc. can be proudly carried. This sort of homey "We care about you!" material used to grow stale in a once-a-month prosaic union newspaper, but can now excite and please members who appreciated the local's positive recognition.

Especially dynamic local union site also offer members a swap service, a garage sale outlet and/or a recipe-exchange page. These and other "down home" services are designated to get members to think first of the local's website when seeking valuable goods, services and information. In this way, virtual bonds are being forged between Labor and its dues-payers, bonds that may yet help keep many members from drifting away, spiritually or actually.

Response #2: Reaching for a new model. Recognition grows that as smart and promising as are the innovations above, they do not far enough. The hardest question Labor confronts asks if it has the will and "smarts" to employ a radically different model, an exercise in "discontinuous" innovation with computer use at its core, rather than its periphery... one I call the F-I-S-T model, its goal a new form of labor organization I call a CyberUnion [11].

If Labor is to have a chance of soon meeting the challenges posed by globalization-based job loss and the embourgeosification of the working class, among many other threats, it must reinvent itself rapidly and thoroughly. A candidate here incorporates four matters newly enhanced by computer uses—namely, futuristics, innovations, services and labor traditions (F-I-S-T).

"Futuristics" would have a CyberUnion employ forecasting to learn where relevant industries are heading, why, and what Labor might do about it. Forecasts would scrutinize demographic changes in the labor force the union and/or local draws on. Forecasts would enable Labor test the warring claims of antagonists who beckon for Labor's support, as in the

Global Warming or Energy embroilment. Above all, forecast would enable Labor to better anticipate training upgrades for members, and continue thereby to distinguish its dues-payers from their less well-prepared competitors.

"Innovations" would have CyberUnions trying this, that and the other thing in a responsible and earnestly assessed pursuit of ever better processes, things, services and so on. The union or local would gain a proud reputation for early adoption of cutting edge items, and members would look to the organization for assessments and advice when considering testing a novel option themselves. Above all, innovations would mark the CyberUnion as forward-looking, self-confident and thereby worth the membership of all intent on making, rather than inheriting a future.

"Services" refer to the ability of CyberUnions to use computer power to vastly enhanced 101 old and another 101 new services of keen value to the membership. Typical would be arranging for the sale of computers and software at great discount, thanks to the volume buying Labor can arrange (as demonstrated already in Sweden, Norway, and elsewhere). Another service might have a local facilitate car-pooling, using a list serve of members computer-sorted by zip code. Or arrange in cyberspace for joint boycott or picketing missions that come off more smoothly and effectively than ever before possible.

"Traditions" refer to the dedication of CyberUnions to honoring the history, culture, and lore of a union and/or local. Every effort might be made to create an oral and video record of the reminiscences of older members, complete with archival storage. Many relevant labor songs, anecdotes and historic speeches might be added to the site, along with streaming video celebrations of special days and events in the organization's past.

Labor urgently needs rewards possible from reliable forecasting: from innovations such as computer data mining, from computer-based services and from computer-aided celebration of traditions. Together, these four items (F-I-S-T) just might help provide Labor go beyond its necessary, but insufficient use of computer strengths [12].

Response #3: Reaching for new leadership: Pivotal here is the possible rise to power soon of a new cadre of leaders, men and women drawn from Labor's own self-schooled computer enthusiasts or, by their jargon title, Labor's digerati. Capable of matching the organizational flexibility and fluidity of their business management counterparts, the digerati are Labor's secret weapon. Although weakened today by a lack of consciousness of kind, networking and leadership, this cadre could soon prove the critical ingredient in assuring Labor's revival [13].

Many of the digerati envision using computers that will provide unprecedented access of everyone in Labor to everyone else... officers to members, members to officers, unionists to nonunionists and vive versa. Aware of the likely arrival soon of computer "wearables," empowering unionists as never before, some of the digerati are busy even now planning to make the most of this.

On the digerati agenda is promotion of the rapid polling of the membership. Spotlighting computer-use models worth emulating, in or outside of Labor's world. Putting electronic libraries at a unionist's beck and call, along with valuable arbitration, grievance and mediation material. Offering open chat rooms and bulletin boards and nurturing the creation of a High Tech electronic (virtual) "community" to bolster High Touch solidarity.

As if this was not enough, the vision of many of Labor's digerati includes a quantum increase soon in the collective intelligence and cooperation among "global village" unionists. They would pursue unprecedented cooperation across national borders, and expect in this way to mount effective counters to transnational corporations.

Forward thinking and visionary, these techno-savvy men and women have a hefty dose of indefatigable assurance and optimism [14]. Unlike many of their peers, their expectations concerning the renewing of Organized Labor are almost without limits. Believing that what they do matters, and graced by a strong sense of purpose, their influence may soon soar.

This cadre receives a valuable boost from a new force on the scene—one Karl Marx envisioned, but lived over a century too soon to employ—a Fourth International-of-sorts, a feasible way for workers around the globe to be in real time contact for real-time concerted industrial action [15]. With an estimated 2700 Labor Union websites online now and more being added weekly, the opportunities for global networking are enormous [16]. American union activists are in an unprecedented dialogue with their counterparts around the globe. (See, in this connection, http://labourstart.org and http://icem.org.)

Guided, then, by a growing cadre of its own "digerati," Labor is steadily learning more about variations on the F-I-S-T model. Experiments with it may help invigorate the membership. Draw in new members. Intrigue vote-seekers. And in 101 other valuable ways, enable a new Labor Movement to provide what union "netizens" increasingly expect of 21st century Unionism [17].

Summary: Labor union prospects? None of the advances possible in Labor's uses of computer hardware and software will suffice unless there are commensurate advances in "thoughtware," that is, in the quality of thinking and imagining in Labor leadership [18]. Their organizations, 5 years from now, are likely to be very different: They may have faltered badly [19]. Or they may draw handsomely instead on CyberUnion attributes (F-I-S-T) [20]. While computerization alone cannot "rescue" Organized Labor, and while job loss to globalization and membership recruiting will long remain trying, unless Labor soon makes bolder use of computer power, its renewal may prove impossible.

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Joe Coates' perspective: Selected quotations from his TFSC columns

Editor's note: Following are selected excerpts from the many "From My Perspective" columns that Joe Coates wrote for TFSC. They reflect Joe's unique, wide-ranging, and insightful opinions on the present and the future. He may be provocative; he is never dull.

Harold A. Linstone, editor-in-chief

On the U.S. Constitution:

The Constitution, which, by much of the world's reckoning, is the finest political instrument ever created, is a superb document of domestic governance. Increasingly, it falters and fails in the face of an integrated domestic society of continental size and the accelerated globalization and integration of all the world's nations over the past six decades ... We must rewrite the Constitution for the twenty-first century and beyond, and that includes starting from scratch, taking nothing as sacred, and beginning the discussion anew.

vol. 38 (1990), pp. 101–106.

On the U.S. Congress:

The Congress has a strong need to reestablish its credibility with the people. My recommended step one is to stop all work in the U.S. Congress for a month and devote a plenary session to the establishment of a vision of the U.S. for the next fifty years ... The people could be their daily audience on C-Span.

vol. 42 (1992), pp. 413–417.

On the termination of OTA:

Infanticide is not unknown in government anymore than it is in private life. But killing off a teenager on the brink of adulthood is more reprehensible. Why? Because performance and potential are visible and undeniable. The U.S. Congress is now on the verge of killing off its Office of Technology Assessment (OTA), a child of its own creation ... If and when OTA goes, Congress will be right back in 1965, dealing with a prevaricating Executive Branch and beholden to information generously dished out by all the special interest groups.

vol. 49 (1995), pp. 321–323.

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The center of [TA] activity has switched to Europe ... where the practice has been in many regards more innovative and creative, but at the same time more piecemeal and expert driven.

vol. 67 (2001), pp. 303–308.

On capitalism:

As I see it now, today's capitalism is empty of ideology and intellectually impoverished. Most economists and political thinkers are hanging on to obsolete categories, harking to beliefs as old as the Republic, whose basic principles, if they were ever met, are no longer met and cannot be met in the future. What is missing ... is a new ideology ... It must present a diagnosis of the present situation, a vision of the future, a route or road to fulfill that vision, and a framework which ... is intrinsically expandable into a worldwide system.

vol. 44 (1993), pp. 419–423.

On economics:

Economics is not one of the helping professions. Its primary strength is not in anticipation, strategic perspectives, or in long-term policy guidance. The strength of economics lies in retrospective theory generation and explanation ... Economists are trapped in their thinking about the role of science and technology in society by having to force fit that role into a model that was developed for other purposes, at other times, and to serve other needs ... Economics cannot adequately illuminate the policy strategies and choices regarding science and technology.

vol. 53 (1996), pp. 227–232.

On rural America:

Only a small fraction of communities in rural America can survive and be healthy ... One solution we see that is straightforward and attractive, has never been tried, and is likely to work, is reaggregating small, unviable communities ... The long-term solution to rural America's decline lies in effective economic linkages to the information society nationally and globally. The single, most important factor in achieving that linkage is the fiber optics wiring of rural America.

vol. 43 (1993), pp. 205–208.

On dealing with complexity:

The thesis is simple. Most people in positions of authority, whether in government, business, ... or international organizations, simply don't know what they are doing when they respond to change ... A second thesis is that these same people in positions of authority simply cannot know what to do ... the traditional failing approaches to dealing with complex issues—that is, with any institutional issues—is that the folks in charge ignore the basic premises of strategic planning that every plan, project, or program should be set up from the beginning with a monitoring element that gives continuous feedback and guidance on real-time redirection and change in plan ... Complexity requires either subtlety of action or destruction of the complex for a fresh start as the only routes to success in its management. Either alternative requires the humility of continual experimentation.

vol. 50 (1995), pp. 249–252.

On technological disruptions:

The most important lesson from 50,000 years of technological disruptions is that the storm has always passed. The disruptions have always settled down ... Because of the growing complexity of our society, it is intrinsic, it is not accidental, it is unavoidable, it is not a failure of preparation or learning, that elected and appointed officials simply cannot know what to do .... Therefore, the way to deal with most situations is to make all public actions experimental ... But where will we find these officials, especially the elected ones, who are ready to acknowledge that they do not and cannot know what to do?

vol. 54 (1997), pp. 111–117.

On science, technology, and human rights:

My thesis is that science and technology, on balance, expand and affirm human rights ... science and technology are the primary and the most certain bases for economic progress in the contemporary era. Even at a slow pace, economic progress occurring in a stable economic and social environment is the best assurance of democracy taking root and flourishing.

vol. 40 (1991), pp. 389–391.

On ethics:

Ethics, as a vogue, has all the earmarks of becoming a plague, much the way lawyers and lawyering have become a blight in the last twenty years. My thesis is that whatever the merits of greater ethical sensitivity, it is unrealistic to expect any large fraction of adults to engage issues in ethical terms at all effectively. As a result, much of the effort is, and will be, misdirected, counter-productive, and lead to confusion or complacency ... My argument is that the implicit training we receive in ethical behavior and the more formal training in interpersonal matters leaves most of us unprepared to deal with ethical issues resulting from relationships of entirely different types involving institutions and their complex and subtle interrelationships ... In summary, have you ever met an ethicist you would trust to run a hardware store, much less shape our lives and institutions? If anything, our ethical concerns must be grounded in solid practical judgment, not obiter dicta spoken by those isolated from any serious cares and concerns and bereft of practical judgment.

vol. 47 (1994), pp. 345–350.

On privacy:

The potential that most of us have for any serious violation of our privacy is quite low and the resources that we would put out to maintain that privacy are at best marginal. The neglected but fundamental approach to controlling business abuses is to monetize privacy, and second, to alter the rights of ownership of many forms of information ... Suppose I am a subscriber to *Time* magazine. *Time* plans to sell my name to other subscription or marketing services. They might offer me three free issues, a 50 cent discount, or some other economic payback ... I would have the choice of saying yes or no ... The second generic solution is to shift the ownership of records ... Medical records should belong to the patient and to no one else.

vol. 58 (1998), pp. 167–174.

On the tough-minded and the tender-minded:

The 19th century psychologist, William James, identified two important categories of people: the tough-minded and the tender-minded. Professional, applied, and academic futurists usually are tough-minded ... [They look] to larger forces of society as the movers of events. On the other hand, there are many others who come into the field occasionally, incidentally, or tangentially as a facet of some specific concern ... The themes of holism and integration could bring the two groups together on common ground. The tough-minded could assist the tender-minded in clarifying their visions; in understanding the scope and range of issues that must be dealt with; in converting the spiritual, mystical, self-transformational into the practical and applied; in linking scientific understanding of holism to the more tender-minded approaches to it; and to look at the large institutions of society such as the city and its material elements and organizational structures as subjects for reform.

vol. 45 (1994), pp. 103–107.

On preparing children:

Over the next twenty-five years, the successful worker must have at least two strings to his or her bow. First will be some undeniable work skill, whether that is as precise as a college degree in electronics engineering or the completion of an apprenticeship program in carpentry. The second string responds to the actuality of white-collar work, the movement toward teams, and the new customer orientation throughout American business. That string is a web of social skills.

vol. 57 (1998), pp. 157–165.

On heroes:

In 18 years of business, I have routinely interviewed job candidates and have asked them, mostly young people under 35 years old, who their heroes are. To a shocking extent I find that the concept is for most of them empty. They have no heroes, no people they can identify as admirable enough to be standards or models for their own future behavior ... Unfortunately the prospects ... are not bright so long as we associate the good things of our society with companies and organizations.

vol. 59 (1998), pp. 305–308.

On materials:

The central new development in materials science is the expanding capability to produce materials to order, combining arbitrary characteristics. Much of the design approach to date has been to treat the electronics or smart capability as an add-on. We will ultimately move beyond the mere add-on toward integration in design-to-be-smart, implying new materials. As devices get smaller and as more attention is given to micromachines and nanotechnology, the critical factor in materials shifts from volume to surface. Surface science will become increasingly important to most industrial processes and products.

vol. 41 (1992), pp. 189–193.

On state and local government planning:

[In doing Year 2000 studies, the various groups] had a clear, sharp view of the trees but proved weak in seeing either the leaves or the forest, that is, in seeing the micro or the long-term macro factors. The midrange issues concerned with housing, education, and welfare were clear and well understood ... [they] almost totally failed to effectively engage the absolute core issue for the future of the city, namely, the long-term economic base of the community ... There also tended to be a broad rejection of the futurist model of thinking.

vol. 42 (1992), pp. 309–316.

On immigration:

My forecast is that, by the turn of the century, Mexican–American political muscle will be exercised in the Southern tier in unprecedented ways ... We see great trouble in the Southern tier in the early part of the next century ... Muslim cultures are on the move into the European and American communities. A third development is the move of both Indian and Chinese immigrants ... into the United States in interestingly large numbers ... My suggestion is for a national commission ... to look at the question of America's polyethnic and polycultural society of the third millennium. We should become what we want to be; but first we must know what we could be.

vol. 39 (1991), pp. 411–415.

On the census:

Since the Census Bureau, like every other government bureaucracy, is incapable of endogenously generated radical change, the most effective way to promote a new basis for the bureau would be a commission on the census of the 21st century ... Private funding must be sought for such activity out of private resources. The census is too important to the future of the nation to be left in the hands of bureau professionals.

vol. 44 (1993), pp. 325–329.

On terrorism:

Terrorism's brilliant future lies in two facts. First, the rapprochement between the East and the West has freed up the world in scores of places for violent actions to settle longtime political disputes. Second, and more significant, in its global spread, is low-cost telecommunications and low-cost transportation, which make it practical to plan, orchestrate, and execute terrorist acts far from the home territory of the parties involved ... What can be done to prevent terrorism? Probably nothing, but surely one can take actions that will contain, reduce, and limit the frequency and severity of actions.

vol. 51 (1996), pp. 295–299.

On flawed forecasts:

Forecasts tend to fail for one of seven interlocking reasons: unexamined assumptions, limited or misplaced expertise, lack of imagination, neglect of constraints, excessive optimism, mechanical extrapolation of trends, and overspecification. My advice to professional futurists or to the user of future studies is to keep these sources of error in mind . . .

vol. 45 (1994), pp. 307–311.

On movies and television programs about the future:

Movies, television, and cable programs about the future have a dynamic range of mediocre to miserable. The most recent affront to viewer intelligence is the series "Future Quest" . . . [it] is not the worst nor the only bad look at the future, but the wisdom of the media moguls and cross-acculturation of directors and producers leads to this continuing downward spiral of repetitive schlock . . .

vol. 48 (1995), pp. 311–314.

On ideal clients:

My ideal client. . .would be an aging billionaire looking to do something important, fresh, different, that would for a long time, if not forever, memorialize his or her contribution to society, based not on the issues of the moment, but on an understanding of the unfolding concerns for the future, using that money to help shape the future and influence the commonweal. Examples: planetary engineering or mega technologies, complexity, new national accounts and quality of life indices, economics of information, and changing nature of work.

vol. 51 (1996), pp. 95–100.

On progress:

There is much to celebrate. Progress toward humankind's full knowledge of, and control of, the earth has been expanding in more directions and at a faster pace in the past five decades than ever before . . . The earth is a system of systems. The farther we push, the more we learn that the skin of the earth is made up of complex systems whose complexities we are steadily coming to appreciate and understand.

vol. 38 (1990), pp. 307–311.

On utopias:

If utopia is taken to be a future ideal state or some imagined general condition of perfection of social, political and institutional, and personal life, then it has no place in contemporary thinking . . . The prominent benefits delivered by technological developments in the 18th and 19th centuries led to the explication of a relatively new concept progress. Unlike the religiously based eschatologies with a fixed end state, the concept of progress does not comfortably lend itself to an end state, only to continued improvements . . . Meanwhile the potential troublesome outcomes of science and technology create a new type of image of the future for which the word "dystopian" had to be coined . . . The dystopian images in films have made it almost impossible for us or our most talented thinkers to conceptualize in positive imagery about the future, with clarity and details comparable to dystopian imagery . . . Would-be utopians must supply complex detailed images of the social, economic, political and personal lives of all people, if they are to have any credibility or have any value to directing the evolution of society. Utopian visions must be at least as grainy and engaging as the dystopian competitors.

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Emerging patterns of complex technological innovation

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Abstract

Technological innovation is increasingly concerned with complex products and processes. The trend toward greater complexity is suggested by the fact that in 1970 complex technologies comprised 43% of the 30 most valuable world goods exports, but by 1996 complex technologies represented 84% of those goods. These technologies are innovated by self-organizing networks. Networks are those linked organizations that create, acquire, and integrate the diverse knowledge and skills required to innovate complex technologies. Accessing tacit knowledge (i.e., experienced-based, unwritten know-how) and integrating it with codified knowledge is a particular strength of many networks. Self-organization refers to the capacity networks have for reordering themselves into more complex structures (e.g., replacing individual managers with management teams), and for using more complex processes (e.g., evolving strategies) without centralized, detailed managerial guidance. Case studies of the innovation pathways traced by six complex technologies indicate that innovations can be grouped into three quite distinct patterns. *Transformation*: the launching of a new trajectory by a new coevolving network and technology. *Normal*: the coevolution of an established network and technology along an established trajectory. *Transition*: the coevolutionary movement to a new trajectory by an established network and technology. Policy makers and managers face the greatest challenge during those periods of movement from one innovation trajectory to another. These are periods of turbulence; they are the embodiment of Schumpeter's "gales of creative destruction." This paper investigates how, in six case studies, core capabilities, complementary assets, organizational learning, path dependencies, and the selection environment varied among the innovation patterns. The paper builds on work reported in a recent book by the authors entitled: *The Complexity*

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1. Introduction

Technological innovation is increasingly concerned with complex products and processes. Complex technologies are those that cannot be understood in detail by an individual and cannot be precisely communicated among experts across time and distance. The trend toward greater complexity is suggested by the fact that in 1970 complex technologies comprised 43% of the 30 most valuable world goods exports, but by 1996 complex technologies represented 84% of those goods [1]. Examples include aircraft and telecommunications equipment. These technologies are innovated by self-organizing networks. Networks are those linked organizations that create, acquire, and integrate the diverse knowledge and skills required to innovate complex technologies. Accessing tacit knowledge (i.e., experienced-based, unwritten know-how) and integrating it with codified knowledge is a particular strength of many networks [2]. Self-organization refers to the capacity networks have for reordering themselves into more complex structures (e.g., replacing individual managers with management teams), and for using more complex processes (e.g., evolving strategies) without centralized, detailed managerial guidance [3,4].

Examples of the kinds of linkages that characterize complex networks are the strategic alliances, joint ventures, and intimate supplier–producer relationships that are proliferating around the world. For instance, *The Economist* reported that some 32,000 new business alliances had been formed in the 3 years prior to April 1998 [5]. Narula and Hagedoorn [6] found 10,000 "technology partnerships" over the period 1980–1994. The networks created by these alliances and partnerships include a wide range of activities, such as sharing production facilities, collaboration in standards setting, and research and development (R&D).

Networks and their complex technologies coevolve. That is, the network shapes the process of technological innovation, and the evolving technology shapes changes in the network [7]. Coevolution involves the interaction of a technology and a network, embedded in a broader technological community, moving along a path, or trajectory. The technological community is comprised of those individuals, groups, and organizations that share a particular model of problem solving for a specific technology trajectory. The community will have general agreement on how to advance the state of the art [8,9]. A trajectory traces the network/technology adaptations that occur during the process of coevolution. Trajectory evolution is the consequence of carrying out the innovation processes that emerge from the members of the network and the larger technological community as they repeatedly strive to push the state-of-the-art. Movement along a trajectory is seldom smooth or uniform; typically the process involves dealing with barriers and opportunities in a "bumpy" fashion [10]. It is the simultaneous evolution of technology and organizations that creates novelty and variety in technological products, processes, and in the networks themselves. The ultimate success of innovation is as much the result of the "selection" of organizational characteristics as it is of technological ones [11].

Complex self-organizing networks are a response to the inability to innovate complex technologies with yesterday's simpler, hierarchical organizational structures and processes. The spontaneous formation of networks reflects a perception of exploding costs, accelerating time pressures, and ever more complicated technical systems as givens in the pursuit of commercial success [12]. Organizational networks provide the means of coping with complexity because they effectively connect individuals and groups that possess the knowledge and skills essential to innovation [13]. Although most individuals and groups involved in the innovation of complex commercial technologies are located in firms, they are often intimately connected in networks to government and university experts, as well as to people in intermediate organizations, such as professional and trade associations, think tanks, or advocacy groups. Whatever their makeup, these networks have unique adaptive abilities [14].

Network relationships are often very complicated, involving not just diverse kinds of formal contracts and licenses, but also many informal knowledge exchanges. These relationships often require high levels of trust and reciprocity, so that communication and learning can take place rapidly and accurately [15,16]. The ability to create networks that can modify themselves quickly is the key to innovative success in a growing number of technological sectors.

The following investigation of how networks carry out the innovation of complex technologies is divided into four major sections. In the first, a five-part framework for network self-organization is presented. The second summarizes the three patterns that characterize innovation. The third analyzes how network self-organization differs among the three innovation patterns. The fourth investigates the challenges faced by policy makers and managers as technologies and networks move from one innovation pattern to another.

2. A framework for network self-organization

Five intertwined factors are evident in the process of network self-organization: core capabilities, complementary assets, organizational learning, path dependencies, and the selection environment.

2.1. Core capabilities

A successful network must hold some core capabilities; that is, it must excel in some aspects of innovation. Core capabilities (or competencies) are the most critical ingredient of innovative leadership, and may range, for example, from systems integration to the ability to conduct R&D in a particular field to the manufacture of a highly specialized product.

Core capabilities have both organizational and technological dimensions. The technological dimension tends to get the most attention because it offers a tangible link to the processes and products that appear in the marketplace [17]. For instance, R&D has been a commonly identified technological core capability. But focusing primarily on the technological dimension offers only limited insight into network self-organization. A more useful picture is offered by viewing core capabilities as those network competencies that make it possible to acquire, create, and use combinations of technological and organizational knowledge in ways that produce winners in competitive markets [18]. For many of those we interviewed in carrying out the case studies[1] this set of competencies was labeled "systems integration." At the heart of successful networks are organizational routines — the patterns of network interactions which deliver successful solutions to particular problems and which are resident in the network's behavior [19, p. 15].

Creating core capabilities is an extremely complex process, well beyond the abilities of an individual firm, university laboratory, or government agency. Not even the largest firm can rapidly develop and integrate all the costly, specialized knowledge and experience necessary for a new or significantly modified complex technology. Networks offer solutions to the problems of complexity, cost, and speed involved in generating and modifying core capabilities.

2.2. Complementary assets

The supplementary bodies of knowledge and skills that networks must access in order to take full advantage of core capabilities are termed complementary assets [20]. For example, where systems integration concerned with increased product performance is a core capability, a network's complementary assets might include distribution or marketing capabilities.

Complementary assets can be either generic or specialized. Generic assets do not need to be tailored to a particular innovation process, while specialized assets must fit with and be integrated into the overall design of the particular innovation. Thus, specialized complementary assets have a high degree of interdependence with the core capabilities, where generic ones do not. These distinctions are important because of their implications for network self-organization. For example, generic assets are usually accessed by short-term, arms-length contracting, in which the supplier of the assets is given little latitude for innovation or self-organization. This is quite different where the holders of core capabilities require highly specialized assets. Here innovation responsibility tends to be dispersed throughout the network to the suppliers of specialized assets. Self-organization and spontaneous improvements in complementary assets can occur more easily when key elements of core capabilities (e.g., design, manufacturing) are shared with valued suppliers of specialized assets over a longer time frame. Gradually the flows of both explicit and tacit knowledge become more symmetrical, trust-based relationships evolve, and the patterns of self-organization become denser.

Conventional contracts may still be an option with suppliers of specialized assets, but the contracts normally will be for longer terms and will try to provide a reassuring context for relationships, rather than just mandating specific behavior. Collective problem solving and

[1] The case studies focused on the following technologies: GE's jet engine turbine blades, HP's cardio-imaging technology, Philips/Sony audio CD, Intel's microprocessor, Sony's microfloppy disk drive technology, and Varian' radiation therapy technology.

greater sharing of tacit knowledge are often requisites for accessing specialized complementary assets [21].

The same kinds of relationships can be established with user organizations that hold valued complementary assets. Frequently, users of process or product technologies possess enough technical and/or organizational knowledge to suggest relevant improvements to the holders of core capabilities. The advanced or "lead" users (i.e., the first to employ a new technology) often are especially expert in generating product or process improvement [22,23]. The complementary assets embodied in lead users' experience (again, often tacit) can be invaluable, especially when user–producer linkages facilitate constant and rapid processes of self-organization.

2.3. Organizational learning

At the heart of self-organization is organizational learning. The organizations that carry out the innovation of complex technologies are networks, that is, intimately linked collections of organizations that commonly include firms, universities, government organizations, and often other types of organizations such as professional associations. A learning network is skilled at developing, accumulating, and transferring knowledge and skills, as well as modifying its behavior and structure to reflect new insights. Self-organization is learning in practice, and the innovation of complex technologies is a network learning process.

Both tacit and explicit knowledge fuel organizational learning. Traditionally, the critical importance of tacit learning has been underestimated; however, it is ubiquitous in complex networks. It resides in individuals and work groups and their processes of interaction and often provides "connectivity" among bodies of explicit, codified knowledge [24].

Network learning involves at least two collaborative activities. First, the search for new problem-solving knowledge and procedures. Self-organization that delivers innovation is heavily dependent on heuristics (e.g., Where do we go from here? Where should we explore? What sort of knowledge should we draw on?) that emerge from insight gained from collective experience [25].

Second, network learning involves experimenting with and redefining innovation problems. Experimentation is about searching for and testing unorthodox ideas, and the possibility of failure is inherent in this process. Experimentation is most beneficial when it takes place in a context that recognizes that failure plays a large role in building knowledge. Successful learning organizations are skillful at incorporating the lessons of "intelligent failure" [26]. One positive lesson frequently involves unlearning; that is, modifying current definitions of problems, methods, and procedures that influence how evidence is interpreted.

2.4. Path dependencies

History matters a great deal in the innovation of complex technologies. Historical details, often apparently minor at the time, can be amplified by positive feedback so that once a technological trajectory is underway it may become entrenched. In such circumstances, even a crisis may not be enough to dislodge a technology and organization buttressed by strong self-reinforcing factors. If positive feedbacks take place rapidly enough and broadly enough, "lock-in" may take place, and the first product technology may be the only one of several possibilities ever developed [27]. Thus path dependence may be a destroyer of technological opportunity. However, past actions taken by innovative networks may also generate new alternatives when experience is used to guide rather than constrain the search for new core capabilities, complementary assets, and learning opportunities.

All aspects of self-organization are to some degree path dependent, and the implications for network competitiveness can differ. As learning takes place and new knowledge and skills are embedded in core capabilities, the network may have more success as competitors find the resulting technologies difficult to imitate. This appears to be especially the case for learning and capabilities that are highly tacit. On the other hand, the development of highly tacit capabilities may mean that new technological opportunities are narrowed. As a consequence, core capabilities may lose their dynamic quality and network innovation may decline [18, p. 565].

2.5. Selection environment

The innovation of complex technologies takes place within a web of interactions among different actors and within a diverse economic, social, political, cultural, and geographical context. Innovation-related knowledge flows take place through both market and nonmarket transactions. Markets exist within the rules and institutions that structure how buying, selling, and production take place [28]. A large amount of learning and technological diffusion takes place voluntarily and informally, independently of economic incentives [29]. Broader social and political structures as well as cultural norms can also exert influence on the directions taken.

The idea of a selection environment draws attention to the fact that the decision to adopt or not to adopt a new innovation may involve consumer preferences, government policies, and a wide set of market factors that range from macroeconomic conditions to the leadership of individual companies [30]. Outside the marketplace, networks seeking to enhance the selection of their innovations frequently find themselves involved in what one study of the industrial biotechnology sector called "institutional engineering" — the process of "negotiating with, convincing or placating regulatory authorities, the legal system, and the medical profession" [31].

3. Emerging innovation patterns

Fig. 1 suggests the relationships among three patterns of complex technological innovation evident in our case studies:

- *Transformation*: the launching of a new trajectory by a new coevolving network and technology.
- *Normal*: the coevolution of an established network and technology along an established trajectory.

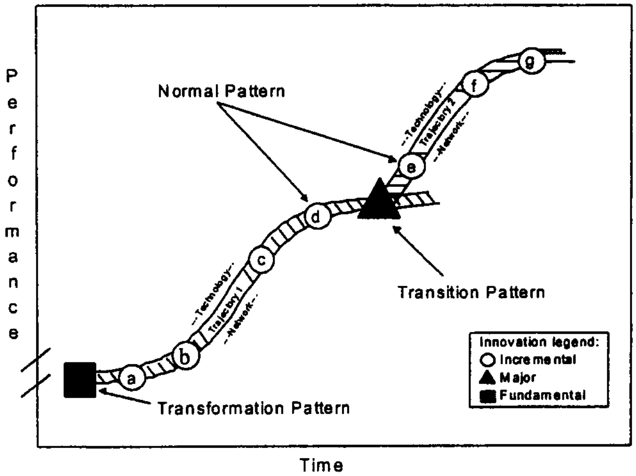

Fig. 1. Three innovation patterns.

- *Transition*: the coevolutionary movement to a new trajectory by an established network and technology.

The square at the lower left illustrates transformation pattern innovations. These are innovations that produce technologies that have fundamentally different characteristics from other technologies. A transforming innovation launches a trajectory; that is, the fundamentally different technology then goes through the series of incremental innovations associated with the normal pattern. The process by which a transformation pattern settles into a normal pattern is illustrated by the series of incremental innovations at points "a" through "d." For most complex technologies, the normal pattern is at some point replaced by a transition pattern, illustrated by the triangle at the intersection of the two trajectories. The transition pattern involves an innovation that produces a major (but not fundamental) change and improvement in the technology. Like the transformation pattern, a transition launches a new trajectory and then settles into the normal pattern illustrated by the series of innovations at points "e" through "g."

The following discussion compares the three patterns in terms of the five factors integral to network self-organization. While the discussion emphasizes differences, the innovations associated with all three patterns nevertheless share important attributes. The most significant common trait is that all complex technologies have deep roots in predecessor technologies. Whether normal, transitional, or transformational, innovations of complex technologies arise from a context that conditions them. For this and other reasons, precise boundaries between the patterns are frequently difficult to draw [32]. Nonetheless, the general patterns are quite distinct.

The starting distinction is that between an established technology or network and a new technology or network. An established technology has the same basic design characteristics before and after an innovation. A new technology features either major modifications in design or the creation of a fundamentally different (transformational) design as the result of an innovation. As used here, technology designs refer to products or processes, or both. Similarly, an established network is one that has the same participant organizations holding the same core capabilities and most of the same specialized complementary assets before and after an innovation. Alternatively, new networks have either the same participant organizations or new ones holding new core capabilities and new complementary assets. It is useful to think of both networks and technologies as complex systems. The linkages among the network members that hold core capabilities and complementary assets are analogous to the linkages among subsystems and components in complex technologies. Changes in these linkages are highly significant for the emergence of new networks and new technologies.

Following the discussion of each pattern a snapshot from one of the cases is presented as an example of the pattern.

4. The transformation pattern

Innovations that are characterized by the transformation pattern generally have one of three origins. First, they flow from the self-conscious search by organizations for new profit making technologies. In an environment where technological innovations are seen as a major route to economic success, the search for transformational innovations is a pervasive part of the rhetoric if not so often the strategies of many technological/business organizations. The transformational innovation that launched the cardio-imaging technology investigated in one of our case studies resulted from Hewlett-Packard's search for new products that could be derived from the company's expertise in medical electronics. Second, transformational innovations flow from efforts to solve problems. The radiation therapy technology case study summarized in Box 1 was started by a medical doctor who was searching for an improved treatment technology. Third, transformational innovations result from serendipity. An example is the Intel microprocessor, which was the unexpected and initially unappreciated result of a search for an improved calculator.

Whatever the origins, the transformation pattern includes the highest risk innovations within the three patterns. The creation of fundamentally new technologies requires that new networks also be formed. The transformation pattern has pervasive and unavoidable uncertainty [33]. Major surprises and discontinuities are frequently encountered, and everything is subject to change within this pattern. Transformational innovations involve development of first-of-a-kind product and process designs. Thus, it is useful to think of transforming innovations as doing more than overcoming existing boundaries; they establish a previously unavailable technology path.

Transformation innovations often involve the fusion of previously separate technologies. Whatever the innovation process when transformation innovations occur great turmoil can result, thus the transformation pattern is frequently associated with the death of a preceding technology and network. For example, US electronic vacuum tube companies did not have the technical or organizational capabilities to enter the semiconductor industry [34].

Table 1
Typical technological and organizational changes in the transformation pattern

Self-organizing factors	Before transformation innovation	After transformation innovation
Core capabilities	Some not existent, some established	New and established
Complementary assets	Established (or none)	New and established
Organizational learning	In diverse unlinked organizations	Cosmopolitan. Broad expansion of search and discovery processes.
Path dependence	None	Weak
Selection environment	Innovation search processes located in organizations	Strong organizational role, limited market role

Table 1 summarizes the changes in the five factors associated with self-organization typical of a transformation pattern.

4.1. Creating core capabilities

Transformational innovations require some new core capabilities. Existing capabilities may be transferred from established technology sectors. New capabilities may in concept be created from whole cloth by fusing previously separate technologies or by tapping into new technology waves (e.g., digital electronics, advanced materials) that spill over a wide variety of sectors or by breakthroughs. In the arena of complex technologies, however, it is difficult to find commercial opportunities that have flowed directly and immediately from scientific breakthroughs. Synthesizing new scientific discoveries into commercial technologies involves connections that are "generally complex and subtle; the lag-times are long and the feedbacks intricate" [35]. The process of synthesis commonly associated with the development of new core capabilities is a risky trial-and-error process. An example was IBM's failure to focus on systems integration when it developed the personal computer. The valuable core capabilities turned out to be microprocessors and software. Not only did IBM fail to anticipate what would happen, so did Intel. An alternative example is provided by Sumitomo Electric's experience with the fundamentally new fiber optics technology. In this case, Sumitomo turned out to have a core capability advantage by synthesizing its established cable-coating competence with the new technology in a way that allowed it to become a leader in the fiber optics transformation [36, p. 29]. Thus, although transformational innovations require new core capabilities, most of those capabilities are the product of complex synthesis.

4.2. Accessing and integrating complementary assets

The transformational pattern requires some new complementary assets. Building a new network normally involves a search for complementary assets that includes exploring, experimenting, and learning that involves accessing a broad range of technological developments. One study suggests that networks develop "fused" or "hybrid" capabilities and assets that make technological fusion opportunities possible. The key in many cases is investing in capabilities and assets that are "seemingly unrelated" [37, p. 227].

4.3. Cosmopolitan learning

A network needs to "be at home anywhere" when approaching transformational learning. When learning must take place in areas that are unrelated to past learning, a network must become cosmopolitan, it must look across a broad map of technologies and technology sectors. In the transformation pattern, learning boundaries expand and become blurred. No potential source of usable knowledge can be ruled out [38]. Undertaking cosmopolitan learning may require linkages to multiple networks cutting across different industries, sectors, and economies. Success is usually associated with a general openness to redefining organizational routines and decision-making procedures [39]. The other side of this is the need for unlearning and breaking with the past.

4.4. Weak path dependence

Technological transformations represent breaks with the past. They therefore have the weakest path dependence of the three innovation patterns. Yet history is not entirely irrelevant even in transformations. This is because the ability to exploit breakthroughs or fusion depends to a very great extent on existing core capabilities, complementary assets, and learning capacities [40].

4.5. Limited market selection

Transformation patterns tend to emerge in the absence of powerful market selection forces. Fundamental innovations have never been seen before and thus have no clearly defined initial market [41]. This was true, for example, of the Xerox technology and of the Intel microprocessor. By definition, fundamentally new technologies must face a market in which there is little user knowledge of what is being introduced. This may lead potential customers to discount the new technology's possibilities. Low user interest may, in turn, reduce the incentives for networks to develop markets aggressively enough. Even when well-defined markets do emerge, it can take a long time (often more than a decade) for them to develop [42]. The weakness of market forces is often cited as a reason why many potential competitors opt out of pursuing an innovation pathway that turns out to be transformational. For example, negative analysis of the market potential of early xerography appears to have been a key factor in the decision by IBM managers not to pursue the innovation of copiers [43, p. 109].

Absent a clear market an organizational commitment to developing the technology is often essential. It is precisely this role that the U.S. Department of Defense has often played in the past. Similarly, "Sony's product-launch decisions [in the previous period] were strongly guided by its chief executive, Akio Morita, who followed his intuition rather than careful market research" [44]. Supportive institutions make it possible to allocate more creative resources to high-risk activities. It is society's institutions, including public policy, that provide much of the innovative foundation needed during periods of transformational change.

Box 1. An example of the transformation pattern: the Varian Clinac

Radiation therapy using cobalt-60, a natural radiation source, came into use as an established cancer treatment during the 1950s. By the mid-1970s, a network centered around Varian, a company created by people who were part of the physics research at Stanford, had led a technology transformation that saw cobalt-60 replaced by artificial radiation from a linear accelerator. The Varian Clinac machine provided for more precise therapy and better beam control. The Clinac technology did not experience the continuous energy decay associated with natural sources of radiation, and it could be shut down and started up as needed. A lead-user physician at the Stanford Medical School triggered the process of coevolution that resulted in the fundamental change in technology. In part, because of his location, the physician was able to recognize that the linear accelerator research technology being developed by Stanford physicists might provide improved cancer treatment.

In 1956 the first prototype of what was to become the Clinac was developed at Stanford and the technology was then moved to Varian, For over a decade, beginning in 1960, the Clinac technology was involved in a transformation pattern. During this period a network of complementary asset suppliers was developed that ranged from a British producer of the magnetron energy source to lead-user physicians. The experimentation that occurred within the transformation pattern benefited from the accumulated learning of both the linear accelerator and cancer treatment communities, but the new technology did not benefit from an established cancer therapy technology path or a clearly defined market. As the trial-and-error process evolved, however, those involved became convinced of the new technology's efficacy.

The movement to a normal innovation pattern, that occurred in the mid-1970s, came only after repeated network and technology adaptations that involved, for example, the development of a user community that included technicians and health physicists as well as physicians.

5. The normal pattern

Innovations that manifest the normal pattern emerge out of an evolving consensus within the network and community that produces and uses the technology. All of our studies were characterized by a general agreement among those involved about the performance characteristics of the next incremental innovation. To be precise, once one or more designs of a technology were established in the market there was little disagreement concerning the characteristics of the next innovation step within that design. The Intel and Motorola microprocessor designs illustrate the case of more than one established design.

Thus, relative continuity characterizes the normal pattern, represented by the curve connecting innovations along its trajectory. This is in contrast to the sharp discontinuities in the other two patterns. Innovations that occur within the normal pattern are incremental, and even those that must deal with the most difficult barriers or sudden shifts in the selection environment do so largely within the current problem-solving model that the coevolving network shares with the established technological community.

Network innovations within the normal pattern have high levels of confidence regarding what problems demand priority and whether and how the problems can be solved. The dominant short-term uncertainties are about how long the process of solving the problems will take and how much it will cost. Self-organization occurs in small steps, as each incremental innovation emerges [45]. Thus, innovations carried out along an established trajectory are less risky than those in the other patterns. When the conditions of greater continuity and surety can be combined with dynamic learning processes, networks have a higher probability of maintaining a competitive advantage. The greatest profits for complex technologies tend to accrue during periods when the network is in a normal pattern, so this is the preferred context of operations for most networks, and the one toward which they migrate.

Incremental innovations along an established trajectory are characterized by technological changes that deliver enhanced performance. For example, the innovations may deliver greater speed, more diverse applications, and lower production costs. By contrast, the network members and their relationships and the designs of both the product and process technologies remain basically the same before and after an incremental innovation. Table 2 summarizes self-organization within the normal pattern and Box 2 offers an example.

Table 2
Typical technological and organizational changes in the normal pattern

Self-organization factors	Before incremental innovation	After incremental innovation
Core capabilities	Established	Established. Some enhancement by way of altered linkages to complementary assets.
Complementary assets	Established	Established, plus any or all of the following: • Reconfiguration of existing assets; • Upgrading of existing assets (e.g., from generic to specialized; from specialized to integration into core capabilities); • Linkages to new assets.
Organizational learning	Local	Local. Often more focused than prior to the increment.
Path dependence	Strong	Strong. Often even more strongly linked to the past than prior to the increment.
Selection environment	Powerful market	Powerful market. Signals more meaningful than prior to the increment.

5.1. Enhancing existing core capabilities

Innovations within the normal pattern generally enhance established core capabilities. The emphasis is on improving existing performance rather than expanding into entirely new areas [36]. Faced with the challenges of innovating complex technologies, most networks gradually enlarge the diversity of their capabilities, but their capability profile remains relatively stable [46]. Deepening and broadening existing capabilities by learning inside the existing network and by accessing an ever-wider array of complementary assets is the normal route to incremental innovation. Core capabilities are often enhanced through the changing utilization of complementary assets and the associated reconfiguration of the network. This process of augmenting core capabilities incrementally has been termed "creative accumulation" [47].

As established networks and technologies coevolve along an established trajectory, core capabilities tend to become more fixed. However, even in mature trajectories, new tacit knowledge and know-how continue to develop as incremental innovations occur. This often is especially evident in an increasing mastery of systems integration and architectural knowledge, which increases the capacity to synthesize previously separate knowledge and complementary assets [48]. Many observers emphasize the particular importance of tacit knowledge to repeated innovations of process technologies (e.g., engineering design, concurrent engineering) during the latter stages of a trajectory [49]. The blend of tacit and explicit process knowledge acquired from incremental innovations has been the foundation for much of the success with lean or agile production systems [50].

5.2. Exploiting complementary assets

In the normal pattern, complementary assets are used to enhance and exploit established core capabilities. Some established assets acquire a higher priority over time and some may even become core capabilities. New complementary assets are often added to networks during normal innovations. As a normal trajectory evolves, however, there is often a growing distinction between specialized and generic assets. Alternatively, the boundary between the most important specialized assets and the network's core capabilities becomes blurred.

Organizational indicators of this blurring process include higher levels of trust between the holders of core capabilities and holders of critical complementary assets. As the normal pattern unfolds, many networks manifest nearly seamless relationships between "first-tier" complementary asset suppliers, priority users, and the holders of core capabilities. Second-tier asset holders, by comparison, tend to evolve toward more formal, arm's length relationships with the holders of core capabilities [51]. But even with more distant second-tier suppliers, the network must retain enough knowledge (e.g., design expertise) to be able to access and use their assets. The holders of core capabilities must maintain an "intelligent customership" for complementary assets [48, p. 1273].

5.3. Local learning

Organizational learning in the normal pattern is predominantly internal to the established network and it tends to become even more focused with each incremental advance. As network routines and heuristics become well developed, learning becomes ever more dependent upon what has been done in the past. Thus, as problems emerge, established networks know where to go for solutions. This makes problem solving a less risky process than it is when more wide-ranging, exploratory learning is required [52]. The local learning in successful networks is highly dynamic and seldom involves just reusing past experiences. Adaptive local learning entails breaking with the past in small but significant ways. Often this involves integrating new knowledge from a variety of projects occurring along the same trajectory, or it may take advantage of synergies emerging from entirely different trajectories. In general, the more significant the incremental innovation, the more difficult it is to recognize the similarities to previous experiences [53].

5.4. Strong path dependence

With incremental innovations, networks learn only what is needed to solve the next problem. Thus, success rests on carrying out relatively narrow and constrained search and discovery activities. Such local learning bounds a network's technological course, and thus bolsters path dependence [37,54, pp. 522–523].

Another way in which local learning enhances path dependence is through reduction of risk and uncertainty. Network learning cumulatively decreases the costs and risks of innovation as the organizational learning process evolves along a trajectory. As choices about where and how to engage in search and discovery activities become better defined, and routines and heuristics become more organizationally embedded, the tendency to continue pursuing the existing pathway strengthens [19,46,54].

5.5. Powerful market selection

Once a network, technology, and trajectory are well established, market forces usually play a significant selection role. At the beginning of the normal pattern, the tradeoffs between alternative incremental innovations may be understood by only a few lead users and first-tier suppliers. Thus, market demand signals may be mixed and conflicting. Well-defined market segments and the relationships between the network and a wider array of users and suppliers usually develop only after extensive incremental learning and adaptation [55].

Eventually, the relative stability of the normal pattern enhances the importance of markets because a consensus develops concerning technological expectations, i.e., the performance characteristics of the next incremental innovation. These expectations, in conjunction with the collection of demonstrated capabilities and embedded routines, provide a relatively solid framework within which a network can read and evaluate market signals.

Box 2. An example of the normal pattern: the GE turbine blade

General Electric's (GE) innovation of blades for high-pressure turbines on jet engines began during World War II. GE entered the turbine blade business at the initiative of the US Army Air Corps. Initial work focused on the forged turbine blade trajectory launched by the British and the Germans prior to GE's involvement. By the mid-1950s, however, a new cast turbine blade trajectory had been launched and all significant turbine blade innovations since have taken place along that trajectory. Over the course of almost five decades since GE began incrementally innovating cast turbine blades, three significant innovations have occurred along the trajectory. Further, within each of these innovations, at least 16 different alloys have been developed in the pursuit of ever-higher operating temperatures. Between 1950 and 1990, alloy-operating temperatures increased from 1550 °F (about 850 °C) to nearly 2000 °F (about 1090 °C).

GE initially held the core capabilities for blade design, development, and use, as well as many of the complementary assets. For several decades GE maintained the capacity to produce turbine blades entirely in house. Its goal was to be able to measure the performance of outside complementary asset suppliers. Initially, the core capabilities were blade design, materials (e.g., alloys) development, and fabrication. Over the past two decades, GE has systematically divested itself of most in-house complementary assets, and its core capabilities now focus on the design of the turbine blade and its integration into the engine. In carrying out the design function, GE has modified its relationship with suppliers. For example, because of the incremental advances in computer-aided design, GE must now work closely in the early design stages with its supplier companies that cast the blades. One result has been the conversion of a substantial amount of tacit knowledge held by the casting companies into explicit knowledge. GE has established new contractual relationships with the casting companies in which the latter pay their own development costs but are given production contracts at the time design begins. Thus, the casting companies have become first-tier holders of specialized complementary assets.

The evolution of the GE network has been further facilitated by the US Air Force's creation of a new supplier of complementary assets. The Air Force underwrote the creation of a software company that could test initial blade prototypes by running computer simulations. The goal was to speed up the innovation process and thus reduce costs. This effort has led to close cooperation between GE and its major competitor, Pratt and Whitney, which also uses the new complementary assets created by the Air Force.

Other adaptations made by the GE network have included the creation of "centers of excellence" organized around specific jet engine subsystems. These centers have integrated responsibilities for everything from research to contracting with suppliers. As a result, GE is now intimately connected at the subsystem level with a range of specialized asset suppliers. These organizational adaptations reflect new kinds of longer-term, trust-based relationships. All the network modifications, however, have taken place within well-established technological boundaries that are highly path dependent. These boundaries reflect, for example, the expectation that improvements in the alloys used in turbine blades will occur in increments of about 50 °F, and that improved airflow designs for blades will be the primary route through which advances in performance will be achieved.

6. The transition pattern

The innovations that occur within the transition pattern often are stimulated by one or some combination of four conditions. First, the network cannot find an achievable incremental innovation that will stimulate new demand in the market, e.g., product differentiation cannot be innovated. Second, a different generic technology is developed that drives a major redesign, e.g., what digital electronics did for audio technology. Third, a new organizational network enters the market with a new core capability that gives it an advantage, e.g., the Japanese auto industry with just-in-time production systems. Fourth, a major change occurs in the selection environment, e.g., regulatory changes that made it possible for MCI to compete with AT&T and thus, use satellites for long-distance telephone service.

Innovations within the transition pattern are usually distinguished by major advances in technological performance, as well as by qualitative changes in design. These innovations commonly modify an established technology in ways that overcome what were thought to be major constraints on development or to take advantage of new capabilities. In either case, a transition enables the technology to perform beyond what was thought to be possible.

In all of our case studies the transitions were characterized by the integration of previously separate technologies. Often the basic technology remains, but there is enough design modification driven by the integration of the previously separate technology to enable movement across a previously insurmountable threshold. Frequently a transition pattern involves modifications in the overall design of a product or production process that results from integrating a new subsystem. One illustration is the transition from propeller to jet aircraft. In this case, the airplane crossed a previously constraining aerodynamic boundary. In the process, a major redesign of airplanes resulted [56]. After the transition, the airplane was not only faster; it took on a new shape.

When previously separate technologies must be integrated to carry out the transition, a new network must be evolved. Often new organizations that provide major new product or process subsystems are added to the existing network. Major innovations, then, add new core capabilities, which may be either held by new participant organizations or developed by the holders of the old network's core capabilities. Significantly restructured network linkages are integral to all such changes in core capabilities and complementary assets.

When transitions take place, networks face significant uncertainty about the design characteristics of the technology and about what the innovation will cost and when it will occur. Nonetheless, major innovations can usually rely on a reservoir of knowledge that has been accumulated by the previously separate networks while carrying out the incremental innovations associated with previous normal trajectories. Thus, a new network resulting from a trajectory transition can have a reasonable level of confidence in its ability to resolve these transition issues by modifying the learning approaches, heuristics, and routines developed in the past.

As noted, transitions may be generated by problems, opportunities, or a combination of both. An example of a problem-generated transition is the perception of the networks moving along the various semiconductor trajectories that they may be approaching a transition because their ability to continue integrating more transistors onto one chip at ever lower costs seems to be confronting impassable technical barriers (e.g., the need for more advanced materials). Concerns about an impending transition have nagged the semiconductor industry for years [57].

A new opportunity example may be the major performance improvements enjoyed by the Boeing network when it adopted new engineering design and manufacturing capabilities (e.g., computer tools for prototyping) in the innovation of the 777 aircraft [58].

A highly visible example of a transition generated by a cross-sectoral movement of technology was the Sony network's innovation of digital electronic imaging as a challenge to the photochemical processes used in cameras [59]. A cross-sectoral transition may appear as a transformation to networks operating in the sector entered by the new technology, although it represents a transition for the network responsible for introducing the innovation. Thus, digital imaging may have seemed transformational to the Kodak network, while it was transitional for the new network centered around Sony.

When networks that have been innovating technologies like semiconductors or advanced materials find broader applications, the technologies can sweep over broad areas of the technological landscape (e.g., into automobiles and manufacturing processes) with major transitional consequences. Increasingly, the competition triggered by these cross-sectoral opportunities emerges in the form of networks that have been called "invisible enemies" [60] or "invading technologies" [59, pp. 158–165]. Whatever the particular factors leading to trajectory transitions, they are never easy [43].

When impending transitions are widely recognized, there are substantial incentives for previously competing networks to cooperate. The great uncertainty associated with transitions is a powerful inducement to establish strategic alliances and other forms of collaboration [13, p. 334]. One factor that encourages cooperation is the belief that limiting the number of transition pathways through the use of voluntary standards setting has advantages for all the networks involved [61].

As with the normal pattern, a transition has characteristic changes in organizational behavior and technology, which are explored more fully below. Table 3 provides a summary of the changes typical of a transition pattern and Box 3 offers an example.

6.1. Expanding and eliminating core capabilities

Trajectory transitions involve some new core capabilities. In most cases, part of the prior core capability profile remains useful, only a portion of the capabilities integral to the former dominant technology becomes obsolete, while previously marginal capabilities may become important [48, p. 1264]. Often some prior capabilities are linked with core capabilities

Table 3
Typical technological and organizational changes in the transition pattern

Self-organization factors	Before transition innovation	After transition innovation
Core capabilities	Established	Partly new, due to some combination of: • Adapting existing capabilities by modifying problem solving approaches and routines; • Adding new capabilities (e.g., cross-sector spillovers); • Eliminating outdated capabilities.
Complementary assets	Established	Partly new; specialized assets are often added.
Organizational learning	Local	Regional. Broadening rather than deepening. Altered heuristics, experimentation.
Path dependence	Strong	Medium. Influence of past depends on where transition arises from.
Selection environment	Powerful	Moderately powerful. Institutions become as important as markets.

developed in another sector to provide a new source of competitive advantage. This highly uncertain set of transition developments contributes to competitors' interest in cooperating.

One way to expand and adapt capabilities is to create new and more dynamic network routines that promote different approaches to problem solving. Another way is to combine older routines in new ways. Although new routines are critical to new networks, they are difficult to develop because they depend so heavily on experience and so often require tacit knowledge. For these reasons there are powerful tendencies to continue using old routines. One point appears clear: in most transitions the changing of routines is inseparable from the process of developing the new network [54, p. 519].

When a transition requires the acquisition of new core capabilities (i.e., knowledge and skills that provide distinct innovation capacities), the need for speed typically means that network learning involves either acquiring explicit knowledge or adding new members to the network. Tacit knowledge integral to new core capabilities generally takes too long to develop internally, so some expansion of the network's organizational boundaries is required [43, p. 111].

6.2. The exploration role of complementary assets

As with core capabilities, a trajectory transition can either enhance complementary assets or make them obsolete. In most cases, new assets are needed, and they need to be linked to useful existing assets, as well as the core capabilities. Because specialized assets are most likely to be made obsolete by a transition, the search for or development of new specialized complementary assets becomes particularly important.

Exploratory assets — those that move beyond exploiting existing capabilities toward opening access to new ones — are integral to a successful transition. But exploration is a difficult balancing act for the network, since the value of the existing asset profile is likely to be uncertain, and since existing assets may bias the search and discovery process. The latter is of major concern. Established networks, relying on assets developed to cope with exiting technologies, may frame transition problems in a manner consistent with their existing asset configuration. Partnering with organizations outside the established communities is one response to this concern [62].

6.3. Regional learning

Organizational learning during a trajectory transition is usually characterized by moving from a narrow but deep knowledge base to one that is broader. Networks expand their scope beyond the local learning of the normal pattern to engage in more exploratory, regional learning. There is a shift to search and discovery activities that are longer term more external to the network, but they usually remain in the same broad technological area, or "region." This shift in learning is particularly difficult. Because the problems encountered in transitions tend to be ambiguous, learning heuristics and routines must be modified or restructured repeatedly. Absent a defined technological community, it is hard to know where to go for relevant problem solving knowledge. A network in this situation must embrace more risky trial-and-error experimentation. Given the greater uncertainty of experiments during a transition, mistakes become an especially important source of feedback [63].

6.4. Medium path dependence

Path dependence erodes during a trajectory transition, but the needed exploratory learning and search for complementary assets is always constrained by the contexts from which the new network arose. The persistence of path dependence during a transition can be both an advantage and a liability. On the positive side, once a network has developed learning experience along a trajectory, it is well equipped to screen its environment to identify technological changes consistent with its underlying capabilities. In effect, path dependence that has focused the capacity for organizational learning can position the network to search for ways to modify its competence base and successfully complete a transition. On the negative side, path dependence may severely limit the ability to move away from local learning and toward regional search and discovery [37, p. 212].

Ultimately, the impact of path dependence on the transition pattern depends on what has been called the principle of "competence relatedness." That is, network success or failure in making the transition may rest on how much difference there is between the competencies required for the transition and the competencies that exist [34, p. 376].

6.5. Moderate market selection

One consequence of the erosion of stability and predictability in a transition pattern is that the market provides less clear signals. When the process of innovation is highly exploratory, the networks that are being modified are less responsive to economic signals because the market has little knowledge about the new performance capabilities being developed. In such situations, linkages to other actors or institutions (e.g., relationships with government, lead users) matter more than market processes because they provide some stability and some limited foundations upon which decisions can be made [64]. A close relationship with professional associations can provide access to broadly based talent and expertise. Government officials can facilitate regulatory or standards approvals. Lead users can identify new capabilities or assets the network should develop [65].

Box 3. An example of the transition pattern: HP cardio-imaging

Hewlett-Packard's (HP) development of an ultrasound-based cardio-imaging technology (CIT) began in the early 1970s and the technology trajectory dominated by the early 1980s. Over the course of the decade and a half following its initial innovation, the CIT went through five significant incremental innovations along the ultrasound-based trajectory. In the early 1990s a trajectory transition took place with the development of a new magnetic resonance imaging (MRI)-based trajectory. A prototype of the MRI-based CIT had been successfully demonstrated by 1995.

The transition from ultrasound to MRI resulted from at least three developments. One was the search by HP for new markets. The second was the development of technical capabilities that would allow the CIT to replace invasive diagnostic techniques with noninvasive ones. The third was the set of routines that drove the HP network to keep innovating when faced with the absence of a clear target for incremental innovation.

The potential benefits of substituting an MRI platform for ultrasound were part of an emerging set of expectations within the broader cardio-imaging community. MRI was a developed technology in widespread use for other kinds of diagnosis. However, HP did not have state-of-the-art MRI capabilities in-house, or within any of its existing networks. For HP, the choice was either develop its own MRI expertise or link with another network.

HP chose to find a partner with MRI capabilities because it did not want to spend the time engaging in an intensive learning process where some of the required knowledge was tacit (e.g., synthesizing product and process designs). Following discussions with several firms, HP joined forces with the Dutch firm Philips, primarily because both sides felt they could develop a sufficient level of trust to carry out the innovation rapidly. Reflecting this confidence, the two firms signed a "statement of principles," which specified that they would evaluate their relative contributions to the innovation after it was on the market and divide the profits of the initial innovation and all follow-on incremental advances based on that evaluation.

The HP–Philips linkage involved the integration of two established networks to create a new network. Philips was the holder of most of the MRI hardware capabilities (e.g., magnets, systems integration), while HP was the holder of the specialized electronics and signal processing capabilities. Lead users in hospitals and medical schools also became part of the network.

When the new trajectory had been demonstrated in prototype form, a corporate decision in HP resulted in its withdrawal from the network, turning the technology over to Philips. This decision was made as part of a redefinition of priorities within HP, even though the innovation was a technical success and was expected to be a commercial success.

7. Toward a future of innovation gaps, traps, and maps

The primary need for highly adaptive network self-organization is when there is movement from one innovation pattern to another. These periods of heightened turbulence are the embodiment of Schumpeter's "gales of creative destruction" [66]. Perhaps the striking difference from the world Schumpeter observed is that transitions have become routine and expected. Nonetheless, the risk of and frequently the disorder caused by transitions have not been reduced by the recognition that transitions must be expected. The challenge faced by policy makers and organizational leaders requires dealing with pervasive innovation gaps and traps that are products of path dependence and changes in the selection environment.

Faced with these risks and uncertainties, network participants benefit from continuously redefining the shared vision of the future direction of innovation within which self-organization can take place [67]. This vision must be based on a mutually reinforcing fit among core capabilities, complementary assets, and organizational learning that provides a unique competitive position.

7.1. Innovation gaps

What you do not know can hurt you in anticipating and responding to impending pattern changes. When an established network and its technology are coevolving rapidly along a trajectory in the normal pattern, the seeds of "capability gaps" or "learning gaps" are being sown. An extensive period of successful incremental innovation can be the worst preparation for a pattern shift because very innovative networks tend to establish learning routines and heuristics designed to ignore or downplay knowledge that seems irrelevant to current core capabilities. Gordon Moore, one of the founders of Intel, has characterized this process as operating on the "principle of minimum information." In his words, "One guesses what the answer to a problem is and goes as far as one can in a heuristic way" [68].

As long as the evolution of the existing trajectory presents only modest problems or actually provides opportunities that are competence-enhancing, operating with minimum information is likely to reinforce network competitiveness. Exploitation can be emphasized over exploration. But if competence-destroying problems or opportunities are encountered, innovation gaps tend to reduce the prospect of a successful trajectory change, often because the task may be more exploratory and thus beyond the network's learning range.

One of the major protections companies can have is to maintain the diversity of expertise necessary to make it possible to rapidly carry out the needed systems integration that will come with the transition. For the companies that hold the primary systems integration capabilities essential to network transitions, it is valuable to maintain in-house a fundamental and integrated understanding of the knowledge that will access elsewhere in the network. This point warrants particular attention because both the contemporary selection environment and the conditions that contribute to success during the normal pattern create major incentives for outsourcing expertise. To the extent possible it is particularly valuable for the organizations that hold the primary systems integration capabilities to "focus on the softer capabilities, leaving the hard ones to suppliers" [69].

7.2. Innovation traps

What you know can also hurt you in making successful transitions and transformations. Old learning may become outdated in a hurry, and not only because of technological advance. Markets may change as a new set of potential customers emerges. New public policies may be adopted. A well integrated set of core capabilities, complementary assets, and learning leaves networks very vulnerable to the changes that underpin competence-destroying transitions or transformations. Nothing may be as hazardous to network innovation success as the fact that previously successful learning, routines, and heuristics can lead to overconfidence as to their future applicability [70].

Innovation traps often mean that exploitation activities drive out exploration initiatives. This is not surprising, since exploitation generates closer and clearer feedback than does exploration [52]. In such situations, core capabilities may quickly become core rigidities, as formerly dynamic routines become static [26, pp. 29–38].

In our case studies innovation traps provided the circumstances in which it was most often beneficial for organizational leaders to step in and force change. These are cases where managers have little to guide them other than intuition. In Andrew Groves words, "when you're caught in the turbulence of a strategic inflection point, the sad fact is that instinct and judgment are all you've got to guide you through" [71]. The most common pattern is to disrupt the existing network, create disorder with the faith that self-organization will produce a new network and technology. Our case studies indicate that under this circumstance self-organization sometimes leads to success, but sometimes it results in failure. We emphasize an important point here. Self-organization is about the search for fitness, but it does not also always lead to fitness.

7.3. Innovation maps

In order for networks to anticipate innovation gaps and traps, they must engage in sophisticated scanning and search initiatives. One aspect of strategic scanning and intelligence gathering that seems especially valuable is the generation of technology roadmaps. Roadmaps, such as those generated by the semiconductor industry, generally represent a collective vision of technological futures, and they serve as broad templates for ways to integrate core capabilities, complementary assets, and learning in the context of evolving selection environments [72,73].

Roadmaps also facilitate open debates about how the selection environment itself might be altered (e.g., implications of new public policies or other external events) [74,75].

Mapping is not the only way to anticipate pattern changes, but it is a start toward gaining insight into the evolution of the self-organizing networks and complex technologies that are likely to dominate at least the early part of the new century we have entered.

But, it is also the case that roadmaps serve as a clear demarcation for investigating what is beyond the roadmap. Our interviews suggest that the "beyond the roadmap" value has been evident in the semiconductors networks as they seek to address the coming transition.

7.4. Makers of policy and strategy

This article has investigated a central, but frequently unrecognized characteristic, of our world of repeated innovations of complex technologies: the requirement for self-organizing networks. It has not separated out the role of policy makers and organizational managers. That is primarily because they are integral to the self-organizing networks. We have, however, emphasized the role of tacit knowledge, and policy makers and managers who use their organizational positions of power to facilitate fitness hold a central component of that knowledge.

Effective management and policy making involves continuous monitoring during the normal pattern and sometimes disruptive intervention when self-organization is resulting in a lack of fitness, such as failure to participate in a trajectory change. Gaps, traps, and maps are metaphors for three reference points essential to playing the policy maker and management roles effectively.

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Modeling stochastic innovation races

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Abstract

We consider a firm moving towards a stochastic final destination to be chosen from a discrete set after a decision period. The decision period itself may be deterministic or stochastic. We assume the firm can move at variable innovation (R&D) speed associated with a monotone nondecreasing variable cost, and it can also stop and move anywhere. There is a fixed cost per time unit "carried" by the firm as well, associated with keeping at the knowledge (technology) frontier. We investigate various types of the firm's optimal trajectory in the R&D race during the decision period. The model is adapted and applied to racing behaviour in the Japanese telecommunication industry. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Innovation; Race; Competition; Strategy; Industrial economics

> The process of innovative competition is like a race in which it is necessary to run and run well to endure and to prosper, but the race is more like a marathon than a sprint. [8]

1. Introduction

Firms' strategic decisions may sometimes change from stage to stage. At any given stage, the next stage may be known to be tentative in nature even when the firm reveals its strategy in private or in public. We may say then that the firm is actually headed towards a stochastic destination. We follow a decision-theoretic rather a game-theoretic line of reasoning, in the

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sense that we look at the individual firm's options against any or all of their rivals. This relates to Kamien and Schwartz's [1] exploration where they showed that the intensity of rivalry between market participants leads to an increased speed of R&D, which is the main characteristic of a frontier race. To motivate the problem, we give a characterization of racing behaviour in Section 2. Since the firm faces extensive uncertainty in its strategic positioning, we assume the decision period is stochastic. However, to formulate the problem, we first let the decision period be deterministic (in finite time) but the destination be stochastic (Section 3). At a further step, we also assume the decision period to be stochastic (Section 4). If the decision period is stochastic, the problem of identifying the optimal trajectory in terms of strategic positioning, i.e., in the plane-based innovation race, is a dynamic optimization problem, which can be solved by dynamic programming or other calculus of variations or numerical methods. In Section 5 and 6, we deal with special issues of racing behaviour among firms. Section 7 draws conclusions.

2. Characteristics of innovation races

The concept of a race is intrinsic to sports events, crossing the finishing line first is everything to a racer, the rewards may be immense by reaching for the gold. In general, if such a race evolves, the race looks like a sequential machine (finite automaton) acting under resource and time constraints, until a winner clearly emerges. A winner may establish himself at the first trials or runs, leaving very little chance for those left behind to catch-up. The situation of competitive rivalry among firms or businesses in high-technology industries may resemble more complex paradigms of a race that appear more difficult to describe than a sports event. First of all, the finishing line may not be sharply defined. It could be a greater market share than any of the rivals attain, it may be a higher profitability given the share or a higher growth potential. In terms of process, it could be even a slow race at the beginning, which might accelerate to whatever the finishing line constitutes of. It may be a race that is open to new entrants along the way, in a dormant, low innovation-driven industry that brings changes to this industry. It may allow moves among rivals, unheard of in conventional races, such as "leapfrogging," "take a breath and recharge" or redefining a new race through mergers and acquisitions, in the course of the given one. Races may be endogenous, induced by changes in innovation patterns, market structures and productivity cycles. All these issues of complexity may justify to set up a racing model that captures many of the essential features. This would be a model of a stochastic race, which is proposed. Let us describe the characteristics of such a race on achieving technological and market supremacy [2]. A finishing line would be ahead of a present technological frontier, which would be the common ground for starting the race.

Let $TF(C)$ be each racing company's technological knowledge frontier, while $TF(I)$ would be the respective industry's frontier represented by the most advanced company as a benchmark. All firms engage in pushing their frontier forward which determines the extent to which movements in the individual $TF(C)$ of the racing firms translate into movements of the *TF*(*I*). While a variety of situations may emerge, the external cases involve either one firm may push the frontier at all times, with the others following closely behind, or all firms share more or less equally in the task of advancing the *TF*(*I*). The first situation corresponds to the existence of a unique technological leader for a particular race and a number of quick followers. The other situation corresponds to the existence of multiple technological leaders. In some industries, firms share the task for pushing the frontier forward more equally than in other industries. This is usually the case, the more high paced and dynamic is the race in an industry. In any race of the sort, "closeness" is an important but relative attribute. The races are all close by construction. However, some might be closer than others. As a closeness measure of the race at any particular time, one could define $c(t) = \sum_0^N [TF(C_t) - TF(I)]^2 / N(t)$ where $N(t)$ is the number of active firms in that industry at time t. The measure thus constructed has a lowest value of 0, which corresponds to a "perfectly close" race. Higher values of the measure correspond to races that are less close. Unlike other characteristics such as the domination period length during a race, innovation when ahead vs. when behind, leapfrogging vs. frontier sticking, which describe the behaviour of a particular feature of the race and of a particular firm in relation to the frontier, the closeness measure is more of an aggregate statistics of how close the various racing parties are at a point in time. The closeness measure is simply an indication of the distance to approach a benchmark, and it does not say anything about the evolution of the technological frontier. To see this, note that if none of the frontiers were evolving, the closeness measure would be 0, as it would if all the frontiers were advancing in perfect lock step with one another.

On the basis of theoretical works on these issues, e.g., Refs. [3–6], there have been attempts to categorize similarities and differences among various races due to a range of behaviour rules in races though very little empirical work has been done to substantiate these claims [7]. The very robust feature that appears to be common to all races is that there is a pronounced tendency for a firm to innovate more when it falls behind in the race. In less dynamic industries, the race seems most prone to catch-up behaviour rather than frontier-pushing behaviour. Further, even the catch-up behaviour evidenced by firms in this race is less aggressive, in that it seldom tries to leapfrog the frontier. Rather, the firms tend to exhibit more frontier-sticking behaviour than the firms in high-technology, fast-paced industries. Overall, these facts seem to suggest that the incremental returns to a firm that occupies the race leader position seem to be lower in the first than in the second category. The first category also tends to be occupied by firms with the most unequal frontier-pushing activity.

By taking the (large mainframe) computer industry as an example, an interesting point to note is that each frontier advance is embodied in a machine that is frequently the product of years of planning. Frequently, the performance target of a computer mainframe is set when the project begins, though there is some uncertainty in the time taken to achieve this target performance. This, in conjunction with the racing behaviour, implies that firms must constantly anticipate their rivals' actions when deciding on their technology strategy [8]. This is marvelously described in the novel by Kidder [9]. Empirical studies confirm that such anticipation does, in fact, crucially impact the targeting decision. This validates the emphasis of strategic interaction placed by the "racing behaviour" perspective.

3. Stochastic race in a deterministic decision period

The problem: On an Euclidean plane, let N be a set of n points (x_i,y_i); $i=1,\ldots n$; let n probabilities p_i; $i=1,\ldots, n$ be given such that $\sum p_i=1$ We use the Euclidean distance on a plane because innovation characteristics are at least two dimensional, that is, it would apply to so-called system products that consist of at least two components. The probabilities will most likely be subjective probabilities determined by the individual firm's chances to position itself, endogenously determined by its distance to the finishing line or its proximity to the next rival in the race. They may be formed by considering the firm's own position in the race as well as depending on the stochasticity of the rivals' efforts. As a first approximation, we may let the firm's R&D investment x_i, in relation to the total investment of its rivals $\sum x_j$, determine the probability $p_i=x_i/\sum x_j$. Let a starting point, point (x_0,y_0) or (point 0) also be given and let $f(S)$; $S\geq 0$ be a function such that

$$f(0)=0, \tag{1}$$

$$f(S)>0;\forall S>0, \tag{2}$$

$$f(S+\varepsilon)\geq f(S);\forall S,\varepsilon>0, \tag{3}$$

and such that except for $S=0, f(S)$ is (not necessarily strictly) convex and represents the cost of racing at speed S; let $F>0$ be given (the fixed time value); and finally, let $T>0$ be given (the decision period). It is required to minimize the following function by choosing $t\equiv(x_t,y_t)$ and S (i.e., choose a point t, to be at T time units from now, and a speed S with which to proceed afterwards, so that the expected total cost to cross the "finishing line" will be minimized:

$$Z(t,S)=FT+f\left(\frac{\mathrm{d}(0,t)}{T}\right)\mathrm{d}(0,t)+\left(f(S)+\frac{F}{S}\right)\sum_{i=1}^{n}p_i\mathrm{d}(t,i) \tag{4}$$

where $\mathrm{d}(i,j)$ is the Euclidean distance between points i and j. We denote the optimal S by S^*, and similarly, we have t^* and $Z^*=Z(t^*,S^*)$. Note that FT is a constant, so we can actually neglect it; the second term is the cost of getting to t during T time units, i.e., at a speed of $\mathrm{d}(0,t)/T$. Now, clearly, the problem of finding S^* can be solved separately, and indeed, we start by solving it.

3.1. The speed race problem

If we look at the list of stipulations for $f(S)$, Eq. (1) only means that we can stop and wait at zero marginal cost (which we first keep as a strict assumption to justify the flexibility of the race). Eq. (2) is evident and Eq. (3) is redundant, given Eq. (1), since if f is not monotone for $S>0$, then it has a global minimum for that region at some S, say $S_{\min}$, where the function assumes the value $f_{\min}\leq f(S)$; $\forall S>0$. Now, suppose we wish to move at a speed of $\lambda S_{\min}$; $\lambda\varepsilon(0,1]$, during T time units, thus covering a distance of $\lambda TS_{\min}$; then who is to prevent us from waiting $(1-\lambda)T$ time units, and then go at $S_{\min}$ during the remaining λT time units, at a variable cost of $f_{\min}$ per distance unit? As for the convexity requirement, which we actually need from S_{min} and up only, this is not a restriction at all! Not only do all the firms we mentioned behave this way in practice generally but also even if they did not, we could use the convex support function of f as our "real" f, by a policy, similar to the one discussed above, of moving part time at a low speed and part time at a higher one at a cost, which is a linear convex combination of the respective f's. Fig. 1 "sums" our treatment of an ill-behaved function (in dotted lines where never used). We will also assume that f is continuously differentiable, see Zang [10] as to why this is not restrictive in practice. Hence, our only real assumption is that we can stop and wait at zero cost, i.e., Eq. (1).

Lemma 1: Let $\bar{f}$(S); S>0 be any positive cost function associated with moving at speed S continuously and let Eq. (1) hold, then by allowing mixed speed strategies, we can obtain a function f(S); S > 0 such that f is positive, monotone nondecreasing and convex and reflects the real variable costs.

Now, since each time unit cost is F, and we can go S distance units during it, each distance unit's "fair share" is F/S. To this, add $f(S)$ to obtain the cost of a distance unit at a speed of S when the firm knows where it is going and requires their fixed costs to be covered. (On the other hand, not knowing what it wants to do means that the firm has to lose the F money or part of it.) Denote the total cost as above by $TC(S)$ or

$$TC(S) = f(S) + F/S. \tag{5}$$

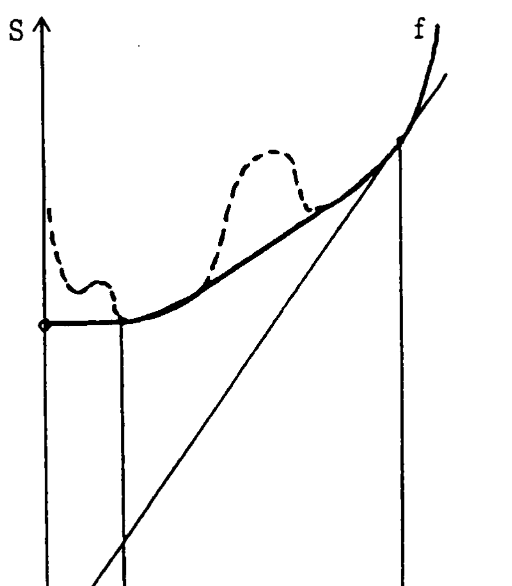

Fig. 1. A well-behaved (fat) and ill-behaved (dotted) speed function.

However, F/S is strictly convex in S, and $f(S)$ is convex too, so $TC(S)$ is strictly convex. Further, $\lim_{\varepsilon\to 0} + TC(\varepsilon) = \infty$, so $TC(S)$ has a unique minimum, S^*. Since we practically assume differentiability, then

$$S^* = \arg\{f'(S) = F/S^2\} \tag{6}$$

and we can obtain it numerically. (S^* is also depicted in Fig. 1, where a ray from the origin supports f.)

3.2. Choosing t optimally

Our problem is to find the point t or the "decision point," where we elect to be at the end of the decision period. Then, we will know with certainty what we have to do, so we will proceed at S^* to whichever point i chosen, at a cost of $TC(S^*)\mathrm{d}(t,i)$. Denoting $TC(S^*) = TC^*$, we may rewrite Eq. (4) as follows:

$$Z(t) = FT + f\left(\frac{\mathrm{d}(0,t)}{T}\right)\mathrm{d}(0,t) + TC^* \sum_{i=1}^{n} p_i \mathrm{d}(t,i) \tag{7}$$

Theorem 1: Z(t) is strictly convex in t.

Proof: Clearly, FT is a constant, so it is convex. Let $h(w) = f(w/T)w$. Hence, our second term $f(\mathrm{d}(0,t))/T\mathrm{d}(0,t)$ is $h(\mathrm{d}(0,t))$. By differentiation, we can show that $h(w)$ is strictly convex, monotone increasing and nonnegative. $\mathrm{d}(0,t)$ is convex (being a norm), and it follows that $h(\mathrm{d}(0,t))$ is strictly convex as well (see Theorem 5.1 in Ref. [11], for instance), As for the third term, it is clearly convex (since $\{p_i\}_{i=1,\ldots,n}$ are nonnegative probabilities), and our result follows for the sum.

It follows that a unique minimum Z^* exists for Z, within the convex hull of the $n+1$ points $0,1,\ldots, n$. In order to find this minimum, we look for a point such that the gradient ∇Z is zero. We now examine the two components of ∇Z by x_t and y_t.

$$\frac{\delta Z}{\delta x_t} = \frac{x_t - x_0}{\mathrm{d}(0,t)} = (f(S) + Sf'(S)) + TC^* \sum_{i=1}^{n} p_i \frac{x_t - x_i}{\mathrm{d}(t,i)}, \tag{8}$$

$$\frac{\delta Z}{\delta y_t} = \frac{y_t - y_0}{\mathrm{d}(0,t)} = (f(S) + Sf'(S)) + TC^* \sum_{i=1}^{n} p_i \frac{y_t - y_i}{\mathrm{d}(t,i)} \tag{9}$$

where (see Eq. (10))

$$S = \mathrm{d}(0,t)/T. \tag{10}$$

The "length" of the gradient L_t is (see Eq. (11))

$$L_t = \left[\left(\frac{\delta Z}{\mathrm{d}x_t} \right)^2 + \left(\frac{\delta Z}{\mathrm{d}y_t} \right)^2 \right]^{1/2}. \tag{11}$$

We can gain some more insight into the problem if we consider two limiting cases : (1) $T \to \infty$ and (2) $T \to 0$.

(1) The $T \to \infty$ case: Here, we assume $S_{\min}>0$. Under this assumption, at a cost of $f_{\min}$ per distance unit, the firm can arrive anywhere during the decision time. Hence, we have $p_0 = f_{\min}/TC^*$, and our problem is solved. As usual, denote the solution point by t^*, and clearly, for T large enough, we are not going to move during the whole decision period but rather only during T^* time units of it, where (see Eq. (12))

$$T^* = \mathrm{d}(0,t^*)/S_{\min}. \tag{12}$$

Hence, the same solution is obtained for any $T>T^*$.

It may be advisable to try solving under the assumption that $T>T^*$ and then check the assumption. This way, even if $f'(s)$ jumps at $S_{\min}$, we will not have any problems with it. If $T>T^*$, we are through, and else we know that $S>S_{\min}$.

(2) The $T \to 0^+$ case: Recall Eq. (5), with S^* as per Eq. (6), we have $TC^* = f(S^*) + F/S^*$, and from Eq. (6), we easily obtain

$$F/S^* = S^* f'(s^*) \tag{13}$$

Now, substitute Eq. (13) to TC^*, and we have (Eq. (14))

$$TC^* = f(S^*) + S^* f'(S^*) \tag{14}$$

Let $W(S)$, as defined below

$$W(S) \equiv f(S) + Sf'S), \tag{15}$$

be the relative weight of the starting point 0 in Eqs. (8) and (9). We observe that $W(S)$ is a monotone increasing function (since f, f' and $f''>0$) and that $W(S^*) = TC^*$. However, at t^*, Eqs. (8) and (9) are zero. Hence,

$$\frac{x_0 - x_t^*}{\mathrm{d}(0,t^*)} W(S) = TC^* \sum_{i=1}^{n} p_i \frac{x_r^* - x_i}{\mathrm{d}(t^*,i)} \tag{16}$$

$$\frac{y_0 - y_t^*}{\mathrm{d}(0,t^*)} W(S) = TC^* \sum_{i=1}^{n} p_i \frac{y_r^* - y_i}{\mathrm{d}(t^*,i)} \tag{17}$$

Squaring Eqs. (16) and (17), adding them and taking the square root again, we obtain

$$W(S) = TC^* \left[\left(\sum_{i=1}^{n} p_i \frac{x_r{}^* - x_t}{\mathrm{d}(t^*,i)} \right)^2 + \left(\sum_{i=1}^{n} p_i \frac{y_t^* - y_i}{\mathrm{d}(t^*,i)} \right)^2 \right]^{1/2}. \quad (18)$$

Clearly, $W(S) \leq TC^*$ (the magnitude of a vector sum is less than the sum of the magnitudes), with equality only in the special case where all the points, including the starting point are colinear, and both 0 and t are to the same side of all the rest (in which case, the firm can behave as if it knows where it is going, since it has to reach the first point at least, and it knows the decision will be made by the time it gets there). However, $W(S)$ is monotone. Hence, if $W(S) < TC^*$, then $S < S^*$ and (Eq. (19))

$$\mathrm{d}(0,t^*) \leq TS^* \quad (19)$$

Following Eq. (18), we define $G(t)$ for any $t\varepsilon\{E^2 - N\}$ (i.e., any point on the plane and 0, but not $i\varepsilon N$)

$$G(t) = TC^* \left[\left(\sum_{i=1}^{n} p_i \frac{x_r^* - x_i}{\mathrm{d}(t^*,i)} \right)^2 + \left(\sum_{i=1}^{n} p_i \frac{y_t^* - y_i}{\mathrm{d}(t^*,i)} \right)^2 \right]^{1/2}. \quad (20)$$

For $t = t^*$ and S chosen optimally, Eq. (18) plus Eq. (20) yield

$$G(t^*) = W(S). \quad (21)$$

Now (for the first time), we use the data $T \rightarrow 0$, and by Eq. (18), we have

$$\lim_{T \rightarrow 0^*} \mathrm{d}(0,t^*) = 0. \quad (22)$$

That is, we only have to determine in which direction and at what speed to proceed, but we will not get very far. The direction we choose is that of $-\nabla Z(t^*)$, as we always have to, but now, we can take 0 instead of t^* using Eq. (22), so we do not have to search for this value. As for the speed, we choose S^{∇} (the "gradient" speed), such that

$$S \triangleq \arg\{W(S) = G(0)\}, \quad (23)$$

since by Eq. (21), this is the value for $t^* = 0$.

Since the speed is one of the parameters we are interested in, we present a theorem, which will also hold for the stochastic decision period case.

Theorem 2: The gradient speed S^{∇} as defined at any point, is an upper bound for the optimal speed at that point, and S^* is an upper bound for S^{∇}.

Proof: By Theorem 1, $Z(t)$ is strictly convex. Hence, along the segment $\overline{0,t^*}$, it is also strictly convex, and since $Z\ (t^*) \leq Z(t)$; $\forall t$, it is monotone decreasing along the segment. Let $g(t)$ be the absolute value of the directed derivative along $\overline{0,t^*}$. Clearly, $g(t)$ is monotone decreasing for c when $t=\lambda_0+(1-\lambda)t^*$ (i.e., $x_t=\lambda x_0+(1-\lambda)x_{t^*}$, $y_t=\lambda y_0+(1-\lambda)y_{t^*}$, 0 being an index and not a number here). For $\lambda=0$, the slope $g(0)$ is bounded from above by $G(0)$, since $G(0)$ reflects the steepest descent (in the direction of $-\nabla Z$). At t^*, the direction of $\overline{0,t^*}$ is the steepest descent direction itself, by Eq. (18). Summing these assertions, we have Eq. (24):

$$G(0) \geq g(0) > g(t^*) = G(t); 0 \neq t^* \tag{24}$$

It follows that the gradient speed S^{∇} is an upper bound on the speed for any movement from 0, and we can designate any point as 0, i.e.,

$$S \leq S^{\nabla} \leq S^*. \tag{25}$$

So S^{∇}, which is rather easy to compute, is an upper bound on our speed anywhere, and it would be easy to extend the proof to the stochastic decision period case using the basic attributes of the expectation.

3.3. The stopping line and the waiting region

For $T \geq T^*$, we obtain $S=S_{\min}$, and by Eq. (15), it follows that $W(S)=f_{\min}$. Using Eq. (21), we have

$$G(t^*) = f_{\min}. \tag{26}$$

Now, starting at different points, but such that $G(0)>f_{\min}$ and $T>T^*$ as defined for them, we should stop at different decision points respectively (unless we start from colinear points, on $\overline{0,t^*}$) each satisfying Eq. (25). Actually, there is a locus of points satisfying Eq. (26), which we call D as follows (Eq. (27)):

$$D = \{t \in E^2 \mid G(t) = f_{\min}\}. \tag{27}$$

We call D the stopping line (although it may happen to be a point). Now, denote the area within D, inclusive, as C, or (Eq. (28))

$$C = \{t \in E^2 \mid G(t) = f_{\min}\}. \tag{28}$$

C is also called the waiting area, since being there during the decision period would imply waiting. Clearly, $C \subseteq D$, with $C=D$ for the special case where one of the points $N0$ is the only solution for a large T. In case $C \neq D$, however, we have a nonempty set E as follows (Eq. (29)):

$$E = C - D (\text{or } C/D). \tag{29}$$

Specifically, there is a point in C, and in E if $E \neq$, for which $G=0$ (if $C=D$, we have to define G as 0 there, since it includes 0/0 terms), we denote this point by $t_{\min}$, i.e., Eq. (30):

$$G(t_{\min}) = 0. \tag{30}$$

Clearly, in order to identify $t_{\min}$, we do not need any information about the starting point or any of the costs we carry but only the information on N and $\{p_i\}$.

We are now ready to discuss the stochastic decision period case. In that connection, note that some of our results so far, such as Theorem 1, the stopping line, etc., are not dependent upon T. Hence, they can serve us for the stochastic decision period case as well.

4. The stochastic decision period case

Our problem is exactly as before, except that T is a random variable (RV) now. Conceivably, the p_i values could be influenced by information such as "the decision has not yet been made," but we do not consider this case in detail (i.e., we assume statistical independence between T and the choice). Our RV may be discrete (contact with management is at predetermined times), continuous or mixed. We discuss the discrete case in detail and show how to accommodate the continuous case by the discrete one. We assume that the distribution of T is given. (Bayesians will find no fault with that assumption, hopefully. Others will have to take it at face value). Let

$$P(T = h_j) = q_j; j \varepsilon J = \{1,2,\ldots\}, \tag{31}$$

where $q_j \geq 0$; $\forall j$ and they sum to one, of course; J may be finite or not, the index 0 is maintained for the start as before, and we may assume $h_0 = q_0 = 0$ for it (Eq. (31)). Our problem is to find the best set of decision points t_j (or t_j^* when optimality is assumed), such that as long as the decision is not yet made by $T = h_j$, we proceed from t_j^* to t_{j+1}^* (starting at $t_0 = t_0^*$). Let v_j be the conditional probability of decision at h_j, given it has not been made yet, i.e., Eq. (32),

$$v_j = P(T - h_j \mid T > h_{j-1}) = \frac{q_i}{1 - \sum_{k=1}^{j-1} q_k}; \tag{32}$$

and following Eq. (7), we define $Z(t_{j-1}, t_j)$;

$$Z(t_{j-1},t_j) = f(h_j - h_{j-1}) + f\left(\frac{d(t_{j-1},t_j)}{(h_j - h_{j-1})}\right) d(t_{j-1},t_j) + v_j TC^* \sum_{i=1}^{n} p_i d(t_j,i)$$
$$+ (1 - v_j) Z_{j+1}(t_j, t_{j+1}^*) \tag{33}$$

This formulation lends itself to dynamic programming very naturally, and assuming optimality, we define $Z_j^*(t_j - 1)$:

$$Z_j^*(t_{j-1}) = \min_{t_j} \{Z_j(t_{j-1},t_j)\} = Z_j(t_{j-1},t_j^*) \tag{34}$$

Before proceeding further with the general solution, two limiting cases will help us to confine our search to a manageable area. These are analogs of cases we discussed above, and here is the payoff for the effort there.

The $P(T<T^*)\rightarrow 0$ Case: This is the analog of the $T\geq T^*$ case, so we proceed at $S_{\min}$ to the correct spot along the stopping line. We refer to the solution as the "slow" trajectory.

The $P(T<\varepsilon)\rightarrow 1; \forall\, \varepsilon>0$ Case: This case, to which we refer as the "gradient" case, is analog to the $T\rightarrow 0^+$ Case, since it stipulates that with probability approaching 1, this is indeed anticipated. Therefore, we move at a speed of S^∇ in the $-\nabla Z(t)$ direction. Now, under the stipulation, the probability that we will go far before the decision is negligible, but this does not deter us from defining the steepest descent or (minus) gradient trajectory all the way until the stopping line. The "gradient" speed we use is a function of t, which may be obtained by

$$S^\nabla(t) = \arg\{f(S^\nabla(t)) + S^\nabla(t)f'(S^\nabla(t)) - G(t) = 0\}, \tag{35}$$

which is a direct extension of Eq. (23).

Since by Theorem 2 (which extends almost directly to the stochastic decision period case), $S^\nabla(t)$ is an upper bound on S. We also refer to this as the fast trajectory. It is interesting (although intuitively clear) to note that S^∇ is decreasing along the fast trajectory.

Lemma 2: When moving along the gradient trajectory, which we denote by X(t), in the $-\nabla$Z(t) direction, S^∇(t) is monotone nonincreasing.

Proof: Let $z(t)$ be the expected distance to the final destination from t given a decision (recall, a decision is due immediately), i.e., Eq. (36):

$$z(X(t)) = TC^* \sum_{i=1}^{n} p_i \mathrm{d}(t,i) \tag{36}$$

Then, $G(t)$ as per Eq. (20) is z's directional derivative along $X(t)$, i.e., Eq. (37):

$$G(t) = |z'(X(t))| \tag{37}$$

We want to show that $G(t)$ is monotone nonincreasing (which will imply our lemma by Eq. (35) and the monotonicity of $W(S)$). We know that $G(t)$ decreases from $G(0)$ to $f_{\min}$ without changing signs along $X(t)$, so it will suffice to show that $z''(X(t))\geq 0$. However, $X(t)$ is a trajectory in the steepest descent direction. Hence, if we differentiate it by t, twice, we get Eqs. (38) and (39):

$$\dot{X}(t) = -\nabla z(X(t))(t). \tag{38}$$

$$\ddot{X}(t) = -\nabla^2 z(X(t))\dot{X}(t) = \nabla^2 z(X(t))\nabla z(X(t)) \tag{39}$$

We continue and differentiate $z(X(t))$, twice again, to obtain Eqs. (40) and (41):

$$z'(X(t)) = \nabla z(X(t))^T \dot{X}(t), \tag{40}$$

$$z''(X(t)) = \dot{X}(t)^T \nabla^2 z(X(t))\dot{X}(t) + \nabla z(X(t))^T \ddot{X}(t). \tag{41}$$

Finally, by substituting Eqs. (39) and (41), we have

$$z''(X(t)) = \left(\dot{X}(t) + \nabla z(X(t))\right)^T \nabla^2 z(X(t))\left(\dot{X}(t) + \nabla z(X(t))\right), \tag{42}$$

which is a bilinear form ($Y^T\nabla^2 zY$) (Eq. (42)). Now, z is clearly a convex function. Hence, $\nabla^2 z$ is positive semidefinite (at least), and our result follows.

Fig. 2 depicts the results of a program run for an exponentially distributed decision period, for seven expectations θ and for seven randomly chosen points of randomly chosen weights (probabilities). For large θ's, the trajectories were virtually the same as the slow trajectory. For small θ's, a similar behaviour was observed relative to the fast trajectory. Interestingly, though all the trajectories were within the convex hull of the area between these two trajectories, one of them actually intersected the fast trajectory. The speed race obeyed Theorem 2. In general, one might say that the faster is the decision due, the faster we should move, and the longer our total trajectory may be—since we do not expect to stick to it for a long while: the slower is the decision due, the more we tend to go slowly and along a "mildly curving" trajectory (if

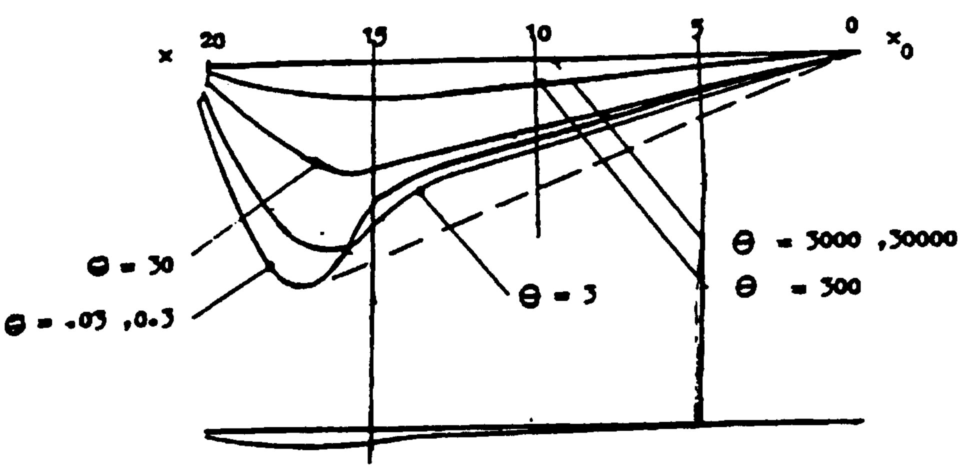

Fig. 2. Exponentially distributed decision period for expectations and for randomly chosen points.

not exactly straight). In any case, as far as the physical location of the trajectory is concerned, we should not find ourselves out of the area defined by the convex hull of the extreme case trajectories, minus E (which we should never enter even if it is in that convex hull). If we do, we can always find a better trajectory for immediate or delayed advantage within this area. We denote this result in Theorem 3.

Theorem 3: One should never leave the convex hull of the slow and fast trajectories, minus E.

Proof: By negation, as described above.

Incidentally, the results in Fig. 2 even show that the convex hull of a "medium" speed trajectory and the slow one contains all the "slower" speed trajectories. However, this may not be extendable to more general distributions, where the relative "speeds" may not be uniquely implied. Note, however, that if we do not use exaggerated vertical scale, all trajectories seem rather straight! Practically, there is no doubt that location wise, we should pick some straight trajectory, even the slow one, and just optimize the speed race. This would yield most of the potential gain, with the additional benefit of a less complex race problem.

If we return now to Eq. (33) or Eq. (34), we can see that the stopping line and the search area are what we need practically to obtain a working dynamic programming model. We may start by assuming the slow trajectory, which would make our decision variable univariate, and we can fold back satisfactorily by assuming that the, say, kth step will bring us to the stopping line. It may happen, that we overshoot the starting point, but it should not be difficult to adjust. However, we do not suggest using this method here, since it does not seem to justify the programming effort, and we can simply use a multivariable library search method instead. A problem might be if local minima exist besides the global minimum; Theorem 4 removes this obstacle.

Theorem 4: The problem of locating the decision points t_j^* so as to minimize $Z_j^*(t_0)$ is convex.

Proof: By iterative application of Theorem 1.

5. Matching an innovation race

In tracking the evolution of part of the Japanese telecommunication industry over several years, it shows that strategic interactions between the firms play a substantial role in determining firm level and industry level of technological evolution. In particular, we identify several "races," each of which is the result of a subset of firms jockeying for a position either as a race leader or for a position not too far behind the race leader. The identification and interpretation of the races relies on the fact that different firms take very different technological paths to reach a common "cycle time" level. In view of the previous description of a stochastic race, it is pertinent to distinguish between two kinds of racing behaviour. A lagging firm might simply try to close the gap between itself and the technological leader at any point in time ("frontier-sticking" behaviour or catch-up race), or it might try to actually usurp the position of the leader by "leapfrogging" it (frontier race). When there are disproportionately large payoffs to being in the technical lead (relative of the payoffs that a firm can realize if it is simply close enough the technical frontier), then one would expect that leapfrogging behaviour would occur more frequently than frontier-sticking behaviour. All attempts to leapfrog the current technological leader might not be successful since many lagging firms might be attempting to leapfrog the leader simultaneously, and the leader might be trying to get further ahead simultaneously. In this regard, one should both report the attempted leapfroggings and the realized leapfroggings. Thus, we may distinguish between two-layer races: in the first one leapfroggings may stochastically occur, and in the second one, followers or imitators may just try to catch up with the frontier, by frontier-sticking behaviour.

6. Multistage races

All the existing work on multistage races is in the patent race framework. Harris and Vickers [4,5] show that the leader invests more than the follower in a multistage patent race scenario. Their result generalizes a similar result due to Grossman and Shapiro [12] for two-stage games. In contrast, instead of analyzing aggregate resource allocation, we discuss how given resources are allocated. In line with the stochastic race model suggested in Sections 3 and 4, there could be an important strategic advantage of being aggressive or fast in each stage of a multistage race. Our focus will be on characterizing the differences in the expected payoff functions of firms as they get ahead of their rivals (or fall behind) and closer to the finishing line. Our explanation here will be intuitive, and analytical treatment is given in Appendix A. We can speak of the monopoly (or duopoly) term becoming more important in a payoff expression as the ratio of its coefficient to that of the duopoly (or monopoly) term rises. It can be established that the monopoly term in the expected payoff expression of the leading firm in a two-firm multistage race becomes progressively more important as it gets further ahead of its rival, provided the lead meets a minimum threshold. The threshold lead is smaller the closer is the lead firm to the finishing line. Conversely, the duopoly term in the expected payoff expression of the lagging firm becomes more important as it falls further behind, subject to the same threshold lead considerations as the leading firm. We assume the leading firm's payoff, when it has finished all stages and is reaping monopoly profits, as a function of the lead it has over its rival. Let the lead firm receive a payoff when it has finished all n stages, and the rival is in the first stage. Then, the coefficient on the monopoly term rises faster than that on the duopoly term as the lead increases. Then, using this property of the coefficients, we consider the leading firm's payoff as a function of its lead, when it is in the last stage of the n stage race. Once again, we show that as long as the lead exceeds a threshold lead (which may be 0), the coefficient on the monopoly term rises faster than that on the duopoly term as the lead increases. A method of recursion can be applied, where the relationship of the coefficients when the lead firm is at stage s of the race is used to derive similar relationships when the lead firm is at stage $s-1$. The procedure is similar for the lagging firm. In this case, we can show that the duopoly coefficients rise faster than the monopoly ones as the lead increases, subject to the threshold lead considerations. The same is shown to be true recursively when the lead position is at position $n-1$, $n-2$, etc. This characterization highlights two forces that influence a firm's choices in various stages: proximity to the finishing line and distance between the firms. The probability of reaping monopoly profits is higher the farther ahead a firm is of its rival and, even more so, the closer the firm is to the finishing line. If the lead firm is far from the finishing line, even a sizeable lead may not translate into the dominance of the monopoly profit term, since there is plenty of time for the lead situation to be reversed and failure to finish first remains a probable outcome. In contrast, the probability that the lagging firm will get to be a monopolist becomes smaller as it falls behind the lead firm. This raises the following question. What kinds of actions cause a firm to get ahead? Intuitively, one would expect that a firm that is ahead of its rival at any time t, in the sense of having completed more stages by time t, is likely to have chosen the faster, less aggressive strategy more often. The monopoly term is increasingly important to a firm that falls behind. Further simple calculations suggest that the firm that is ahead is likely to have made less aggressive choices than the firm that is behind in the race.

A further interesting question is whether a lead results in greater likelihood of increasing lead and then in an increased chance of leapfrogging (as in a frontier race) or in more catch-up behaviour (as in a catch-up). The existing literature [4,5,12] has suggested that a firm that surges ahead of its rival increases its investment in R&D and speeds up while a lagging firm reduces its investment in R&D and slows down. Consequently, these papers suggest that the lead continues to increase. However, when duopoly competition and dichotomy of the race (in frontier pushing and frontier sticking behaviour) are accounted for, the speeding up of a leading firm occurs only under special circumstances. In high-tech industries, such as computers and telecommunications, it could be expected that monopoly profits do not change substantially with increased aggressiveness, but duopoly profits do change substantially with increased aggressiveness. Then, a firm getting far enough ahead such that the monopoly term dominates its payoff expression will always choose the fast strategy, while a firm that gets far enough behind will always choose the slow and aggressive approach. Then, the lead is likely to continue to increase. If, on the other hand, both monopoly and duopoly profits increase substantially with increased aggressiveness, then even large leads can vanish with significant probabilities.

7. Conclusions

Our stochastic model of a race embraces several features that resemble moving objects towards a stochastic final destination. In contrast to game-theoretic treatments of racing behaviour, we look into racing patterns of individual firms in view of their strategic responses to their racing environment. Among those features, we identified the speed race problem, the selection of an optimal decision point t^*, to optimize a gradient trajectory (of technological evolution) and to determine the "stopping line and the waiting region." Such model would be compatible with observations on innovation races in high-technology industries, in particular, with race-type behaviours such as leapfrogging and catch-up, striking a balance between moving ahead and waiting. The model can be improved by incorporating constraints into it. For example, constraints on an innovation path could be given by roadblocks such as a bankruptcy constraint or an R&D uncertain payoff constraint. Some of these constraints may be conceptually easy to introduce, while others may be tougher such as an investment constraint if the total innovation effort en route to t^* plus the worst case would violate it. In such a case, one may want to weight the distant finishing line unproportionally.

It is interesting to speculate on the implications of the way the firms in major hi-tech markets, such as telecommunications, split clearly into the two technology races, with one set of firms clearly lagging the other technologically. The trajectories of technological evolution certainly seem to suggest that firms from one frontier cannot simply jump to another trajectory. Witness, in this regard, the gradual process necessary for the firm in the catch-up race to approach those in the frontier race. There appears to be a frontier "lock-in" in that once a firm is part of a race, the group of rivals within that same race are the ones whose actions influence the firm's strategy the most. Advancing technological capability is a cumulative process. The ability to advance to a given level of technical capability appears to be a function of existing technical capability. Given this path dependence, the question remains: Why do some firms apparently choose a path of technological evolution that is less rapid than others? Two sets of possible explanations could be derived from our case analysis, which need not be mutually exclusive. The first explanation lingers primarily on the expensive nature of R&D in industries like telecommunications and computers, which rely on novel discovery for their advancement. Firms choosing the catch-up race will gain access to a particular technical level later than those choosing the frontier but will do so at a lower cost.

Appendix A. On the expected gain by the model

Our model is based on the fact that the decision period is going to be completely wasted, unless we utilize it. This places an obvious upper bound on our expected gain (V), namely (see Eq. (A1))

$$V \leq FT \tag{A1}$$

In the stochastic case, similarly

$$V \leq FE(T) \tag{A2}$$

Clearly, the only way we can approach this upper bound is if $G(t)$ approaches TC^* along the trajectory throughout the decision period, for instance, if the points are close to each other and far from the start. In this case, we behave as if the destination is known. However, in both the deterministic and the stochastic decision period cases, if T is large, we cannot do anything at least part of the time. It is obvious that in the deterministic case, the gain cannot exceed FT^*, which makes us rewrite $G(t)$, and similarly Eq. (A2).

$$V \leq F_{\min}\ \{T,T^*\} \tag{A3}$$

$$V \leq F_{\min}\ \{E(T),T^*\}. \tag{A4}$$

However, suppose now that $T \geq T^*$, can we really expect to gain even FT^*? The answer of course is no. In this case, $G(t)$ is rather low, at least towards the stopping line where it reaches $f_{\min}$. We may compute V for this case by the following formula (Eq. (A5)):

$$V = TC^* \left(\sum_{i-1}^{n} p_i(\mathrm{d}(0,i) - \mathrm{d}(t^*,i)) \right) - f_{\min}\mathrm{d}(0,t^*), \tag{A5}$$

where the gross gain is the improvement in the expected "future" total costs to reach the final destination, but we have to subtract the "present" variable costs, in this case $f_{\min}\mathrm{d}(0,t^*)$. By substituting $f(\mathrm{d}(0,t^*)/T)\mathrm{d}(0,t^*)$ for these costs, we obtain the expected gain in the deterministic case (Eq. (A6)).

$$V = TC^* \left(\sum_{i-1}^{n} p_i(\mathrm{d}(0,i) - \mathrm{d}(t^*,i)) \right) - f(\mathrm{d}(0,t^*)/T)\mathrm{d}(0,t^*). \tag{A6}$$

In the stochastic case, similarly, we have the following result (Eq. (A7)).

$$V = FE(T) + TC^* \left(\sum_{i=0}^{n} p_i(\mathrm{d}(0,i) \right) - z_i^*(0). \tag{A7}$$

A similar result can be obtained at any stage, given that we reached it without decision, but we omit it. Note, however, that this expected gain is monotone nonincreasing. For instance, once we reach the stopping line, it drops to zero, since there is nothing useful we can do any more. Note that if we start anywhere in C, all the formulas above, including the bounds Eqs. (A3) and (A4) yield $V=0$ (e.g., $T^*=0$ in this case).

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Technological generalizations and leitbilder—the anticipation of technological opportunities

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Abstract

Recent national technology foresight studies as well as the Millennium Project of the American Council for the United Nations University are very much based on "nodes of discussion." These short statements are called, e.g., topics, issues, or developments. This article provides a framework for the classification and analysis of nodes related to future technological development. Key concepts of the article are "technological generalization" and "leitbild." The topics in the technology foresight Delphi studies can be seen as different kinds of generalizations from already realized technological developments. Leitbild is a German word. Its most general meaning is a guiding image. Like a common vision, a leitbild creates a shared overall goal, offers orientation toward one long-term overall goal, and provides a basis for different professions and disciplines to work in the same direction. The analysis of leitbilder and emerging technological paradigms might contribute to the construction of topics and issues and to the argumentation processes related to them. © 2002 Published by Elsevier Science Inc.

Keywords: Foresight; Delphi; Technology foresight; Technological paradigm; Technological generalization; Leitbild; Weak signal; Millennium project; Nanotechnology

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1. Discussion nodes of global learning processes

In the 1990s, there has been a "boom" of extensive national technology foresight studies based on the use of the Delphi method. Another important recent application of the Delphi method is the international Millennium Project organized by the American Council for the United Nations University [1–3]. A common feature in these two highly interesting developments in futures studies is that they are largely based on "nodes of discussion."[1]

The nodes of discussion have typically been short statements, e.g., topics, issues or developments. On the one hand, the nodes have been evaluated by experts using different types of scales related to their validity or relevance. On the other hand, they have been starting points for further argumentation. In the era of the Internet, discussion based on comparatively stable nodes of discussion seems to be a very reasonable approach. The nodes help in the coordination of common learning processes. In the global brain, they are like functional groups of nerve cells in the human brain [4].

Just because the nodes of discussion are so vital for global learning processes, it is highly important to discuss the kinds of properties that the nodes should have. In the Millennium Project, besides different types of issues, the nodes have also presented developments, opportunities, actions, and impediments to timely decision [5]. In national foresight Delphi studies, all nodes of discussion used to be called 'topics' [6–9]. Particularly in Japanese technology Delphi studies, the topics have focused only on technology-related matters: "In principle, topics that have no technological elements and are connected only to socio-economic conditions should not be included in the survey" [9]. The main goal of this article is to discuss some reasonable starting points for the construction of nodes of discussion or topics that are technology related. Actually, there are few important global developments without at least indirect links with technological development.

In comparison with the nodes of discussion in the Millennium Project, the contents of the topics used to be more diffuse in the national technology Delphi studies. It is interesting that many studies have given no definition of a topic. Even in the special issue of *Technological Forecasting and Social Change* on national technology foresight projects, one cannot find a clear definition of a topic [1]. A relatively old Japanese definition of a topic was the following [6]:

> Topic refers to technological breakthroughs, events, or changes, each expected in the future of Japan, some of which may already have taken place outside of Japan. In the latter cases, this refers to domestic realization through the introduction of technology from abroad or international joint development.

One interpretation is that topics are "mini-scenarios" or visions that are believed or not believed by experts. One can find this idea in the report of the last German national Delphi

[1] The concept "Node" was used in the Millennium Project to refer to local units involved in the process. Its 11 Nodes are groups of individuals or institutions that, e.g., identify knowledgeable and creative people in their region. In an analogous way, "discussion nodes," as we use the concept in the main text, might collect people interested in similar issues.

study [7]: "For these topic fields, altogether 1070 future visions were raised. In the topic areas (*Themenfelder*) 1070 visions of the future have been constructed in the form of topics (*Thesis*) ...."[2]

It might be a good idea not to give too restrictive a definition of a technology-related topic. We consider, however, that there are two basic reasons for further delineation of the concept. Firstly, in order to achieve reasonable evaluations, implicit assumptions related to the topic have to be made as evident as possible. We will suggest that the concept "technological generalization" might be useful for that purpose. Secondly, the evaluations of experts are based on their technological paradigms or "leitbilder." Both the construction of the topics and the analysis of results will benefit, if these leitbilder are discussed.

2. Emerging technological paradigms and leitbilder

Though there have been differences in the national technology foresight studies, the median evaluation concerning the realization time of topics has been about 15 years [9]. Especially if we talk about topics with anticipated realization times of more than 15 years, we are often talking about achievements based on emerging technological paradigms. The Kuhnian notion of "paradigm" is commonplace nowadays. Dosi was the first to introduce the notion in technology studies. He assumed that "normal" technological change consists of incremental, relatively small improvements that follow bigger, revolutionary (and therefore "scarce") technological breakthroughs and ultimately result in new technological paradigms. Dosi has characterized a technological paradigm as including both those directions of technological change that you have to pursue and those which you have to neglect [10]. He defined a technological paradigm as a

> "model and pattern of solution of selected technological problems, based on highly selected principles from natural sciences, jointly with specific rules aimed at acquiring new knowledge.... A technological paradigm is both an exemplar—an artifact that is to be developed and improved—and a set of heuristics" [11].

Since Dosi, the notion of "technological paradigm" has been used by so many researchers that even this concept has become commonplace (see, e.g., Ref. [12]). Substantial qualitative

[2] Though "topics" have been used in most national technology foresight projects, their classifications have varied. A possible starting point is that basic concepts of a Delphi study should be based on expertise. Kuusi [8] has suggested a four-level classification of statements in a Delphi study. First we have topics. They are typically statements (e.g., future events or descriptions of technologies) that experts evaluate. Topics are classified under issues including many topics. The topics of an issue are at least partly mutually exclusive alternatives. Issues are classified under issue areas. The idea of an issue area is that typically the same Delphi panelists are special experts (e.g., based on work experience) in the given issue area. It is sometimes reasonable to classify areas of issues into issue fields. The distinctive feature of an issue field is that typically the same panelists are general experts in an issue field just as the same panelists are special experts in an issue area. The general expertise of an issue field does not mean that the expert knows details of all the issue areas in the issue field. It is enough that a general expert can evaluate the validity of arguments of special experts. For example, education might be an issue field and basic education an issue area.

and theoretical work is available on the emergence of a new technological paradigm. Debackere et al. have suggested that a technological paradigm typically emerges in two phases: bootlegging and bandwagon [13].

During the bootlegging period, which may last for a long time, a small number of researchers dedicate themselves to furthering the field. Their peers may not share their enthusiasm. Not infrequently, researchers from such an emerging community have to face severe criticism. Typically, they have difficulties in securing adequate funding; hence, the term 'bootlegging.' Usually, a few isolated individuals start working on similar problems with roughly similar ideas.

Researchers who are dedicated to a new and unorthodox field of inquiry often face a difficult dilemma. On the one hand, before receiving resources, they need more proof that their work will yield results. On the other hand, without resources, they are unable to do precisely that. 'Bootlegging' enables fledging research to proceed without the full knowledge and scrutiny of managers and other researchers, up to a point at which the promise of the idea becomes clear. During this phase, then, the community will be highly concentrated among a small number of organizations, and the yearly increase in number of researchers will be fairly moderate.

As the number of individuals working on the same problem area increases, a communication network emerges with ties that are much stronger than the ties binding the individuals to the organizations they formally belong to. During this second, so-called bandwagon phase of the community life cycle, a very steep increase occurs in the number of researchers working in the community, with this taking place over a relatively short period of time.

As the community grows, a new paradigm comes into being, which is seen by the higher-level network of the (sub)discipline as competing with the older paradigm. The community tries to organize congresses and found journals, so as to be able to steer the selection process. The R&D community is typically distributed across organizations, sectors, and countries. If the work of the new community seems interesting from a commercial point of view, some scientists may be recruited by enterprises, while some who already work within industry are allowed to devote their efforts openly to the new field. Finally, some scientists may decide to become entrepreneurs themselves.

In terms familiar to the field of futures studies, one can compare the new paradigm in the bootlegging stage with a weak signal that only few take seriously. In the bandwagon stage, it develops towards a strong signal that has to be taken into account.

A concept that illustrates the guiding function of an emerging technological paradigm is the "leitbild." Leitbild is a German word. Its most general meaning is: "Leit-Bild-ein Bild, das leitet": a guiding image. Marz and Dierkes describe this phenomenon more closely.[3] Like a common vision a leitbild creates a shared overall goal, offers orientation toward

[3] According to Marz and Dierkes [14], a leitbild has two functions, guidance and image. The guidance function consists of three subfunctions: (1) creating a shared overall goal, or 'collective projection'; (2) orientation toward one long-term overall goal, or 'synchronous preadaptation'; (3) working in the same direction, or 'functional equivalency.' The image function consists of three subfunctions: (1) cognitive activator; (2) providing a focal point, or 'individual activator'; and (3) 'interpersonal stabilizer.'

one long-term overall goal, and provides a basis for different professions and disciplines to work in the same direction. Leitbild refers not only to a common vision of actors. It relates also to the concept of autopoesis (from the Greek: self-organization) functioning as an interpersonal stabilizer. With an efficient leitbild, no center is needed that urges or pressures functions upon the individuals or permanently controls them as they, respectively, carry out certain functions.

Inspired by Marz and Dierkes [14], we want to characterize the crude rules of an emerging paradigm as a system of leitbilds. An emerging technological paradigm is typically a system of many competing leitbilder (system of leitbilder). In the bandwagon stage (or in the paradigmatic stage), one or another leitbild often begins to dominate. Leitbilder are used in visions but it is important to see the difference between the "leitbild" and the "vision."[4] There is a kind of "intellectual community" among followers of a leitbild, but just because the visions of actors having the same leitbild often differ, this intellectual community is often not a real R&D community. The intellectual community of a leitbild typically integrates several communities and members of several communities.

3. Technological generalizations

Next we suggest a further interpretation of the technological paradigm, which seems useful for anticipating future applications of an emerging technological paradigm.

Kuusi suggests that a technological paradigm is a "shared generalization language" capable of producing important generalizations [8]. These generalizations are based on a cluster of linked technologies. The language of a promising technological paradigm can be viewed as a cluster of realized and promising targets and techniques. Realized targets are existing artifacts—or, more precisely, their properties or functions—while realized techniques can be understood as production processes and design methods. The underlying idea of the generalization concept is that existing techniques and targets serve as a platform for a process generating technological options in a multitude of ways. Generalizations are always based on perceived similarities. Emerging paradigms provide similarities based both on realized targets and on realized techniques. On the other hand, a technological paradigm is the result of this type of generalization process, its successes and failures. Realized targets, which have been achieved with realized techniques ("successful exemplars"), as well as unsuccessful exemplars, are "concepts" of the generalization language.

Fig. 1 illustrates different types of generalization. Realized techniques can be directly generalized into promising similar techniques (arrow #1). This means that certain techniques are scientifically similar. From the point of view of the paradigm there are no fundamental

[4] The main difference is that the "vision" in the framework of visionary management is an actor-related concept. Persons or organizations might have visions that give them the ability to plan or form policy in a farsighted way. A leitbild is not related to any specific actor. It is a principle that can be selected as a part of a vision; e.g., a firm might select "the sample principle of digital technology" (a leitbild) as a part of its vision.

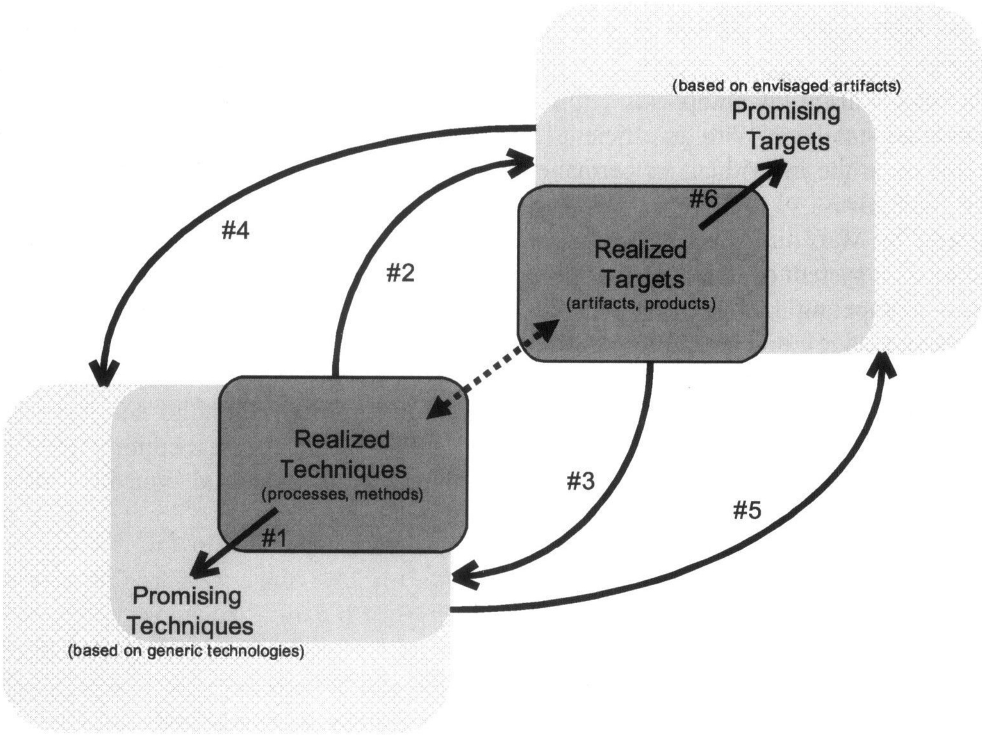

Fig. 1. The "generalization language" of a technological paradigm.

technical problems in a #1 type of generalization. It simply requires some effort. For example, when you have realized that you can use a certain virus to transfer a gene to a bacterium, it is reasonable to believe that you might also use another (similar) virus for that purpose.

Another form of generalization is based on already realized techniques that have the potential to go beyond their current range of application. Techniques can be used to create new artifacts that are (from the point of view of the paradigm) similar (arrow #2). Like #1, this generalization is based on scientific similarity, but only partly. For example, when you have realized that you can use a virus to transfer a gene to a bacterium, it is reasonable to believe that you might transfer the gene in a similar way to another bacterium. But is the transfer of the gene to the other bacterium as acceptable to your customer as the first transfer? The targets (or the transfers) might be very similar from the point of view of the technique but very different from the point of view of your customer. Your customer might consider that the second transfer is irrelevant or even unethical. It is important to realize that technological paradigms as "generalization languages" can also include similarities based on customer values.

When you have realized a target or made a new artifact using a technique, it is natural that you start to think about new ways to produce the artifact or new techniques to improve it (arrow #3). This is a new line for technological generalizations, or for enriching the "paradigmatic language." You might eventually include in your paradigm new techniques that have technically very little to do with your original techniques. Consider fusion energy. The original technical idea of the fusion bomb has very little in common with the recent techniques based on the use of huge magnets.

Generalizations based on processes #1, #2, and #3 are relatively well grounded. It is, however, possible in the language of a paradigm to make generalizations that are far less grounded. Instead of strong scientific similarities, they are based on possible social developments or on weak scientific similarities (weak scientific or technical signals). One might anticipate techniques that might become promising if somebody would first realize certain targets [arrow #4]. For example, if you are able to set up a permanent colony of people on the moon, then, for example, new efficient ways to produce solar energy on the moon might become possible. Or you might anticipate new targets that would be achieved if you could realize a technique that is supported only with weak technical signals [arrow #5]. For example, if you could produce fusion energy cheaply using magnets, you might have sufficient energy for the process that provides an abundant supply of fresh water from salt water.

We have a further arrow in our picture [arrow #6]. Could you generalize in a reasonably direct way from a realized target to another promising "similar" target? Our answer is negative: such generalizations are irrational and have often resulted in very questionable processes. We consider the huge amounts of money lost on the development of the fusion power as a consequence of that kind of generalization. If all that money were to be used for more reasonable generalizations based on solar power, the energy situation of humankind would be much better.

Decision makers and even many scientists have considered that you could proceed from fusion bombs to commercial fusion power, similar to the way in which it has been possible to proceed from fission bombs to commercial fission power. The point is that these apparently similar targets are actually very different from the point of view of the technique used in the fusion bomb. In order to produce commercial fusion power, you have to keep the fuel for a relatively long period at extremely high temperature and under equally high pressure. That is not needed in the fission bomb.

We illustrate the connection between the construction of topics in the national technology foresight Delphi studies and the types of technological generalization shown in Fig. 1. For this purpose, we use the 50 topics that received the highest rankings in importance in the sixth Japanese survey [9]. Because most Japanese Delphi panelists evaluated these topics as important, we can safely conclude that the realization times of the topics are mainly based on technological matters and not, e.g., on ethically questionable objectives associated with the topics.

We have classified the topics according to the six types of technological generalization. Apart from the content of the topics, the illustrative classification is based on the anticipated realization times of topics. The forecast period of the sixth Japanese survey was 30 years from 1996 (the year the survey was conducted) to 2025. If the median panelist anticipated that a topic would be realized during the first 15 years (before 2011), it is reasonable to suppose that the generalization was based on strong technical similarities perceived by panelists. Either the anticipated technique was supposed to be similar to a realized technique (#1) or it was anticipated that a realized technique could be generalized to a target similar to earlier applications of the technique (#2).

If the median anticipated realization time of a topic was in the period 2011–2025, it is reasonable to suppose that evaluations were based on uncertainty about social developments or on weak technical or scientific signals perceived by the panelists. This implies that those topics were mostly based on Types #4 or #5 generalizations. It is, however, possible that a social development making #4 possible might be realized even earlier than 2011. Because the achievement level of targets is higher in #4 (promising techniques, when some targets are realized) than in #3 (techniques that improve the achievement of already realized targets), it is reasonable to suppose that topics based on Type #3 generalizations will usually be realized earlier than those based on #4. The indicative feature of the Type #6 generalization is its very late anticipated realization time. This lag occurs because panelists have no idea how to realize its target(s).

Of course, the information concerning anticipated realization times is available only after a foresight survey. However, a preliminary classification of topics into the above categories might already be possible even before a survey. Typically, Delphi managers already have hints concerning perceived similarities and the reasons for them in an early stage of a Delphi survey. In the future, they might systematically collect such reasons before an extensive survey by looking into the leitbilder of the panelists. The Argument Delphi presented by Kuusi [8] might be useful in that type of activity.

Table 1 includes results of our illustrative classification of the 50 topics. We can explain most of the average anticipated realization times of different types of generalization mainly by means of the considerations outlined above. There are, however, exceptions. For example, the topic "Development of drugs capable of preventing the occurrence of certain types of cancer" is included in category #5 even though its forecast realization time was 2010. In 1996, there were only weak scientific signals based on the Human Genome Project for the realization of this topic.

It might be illuminating to explain our classification of example topics according to the categories in Table 1.[5]

Partly based on the anticipated realization year of 2010, we judged that the experts considered development of solar cells capable of maintaining 15% efficiency for at least 10 years without light convergence to be a continuation of a well-established technological trend. Similarly, it was anticipated that practical use of a highly secure next-generation internet would already be realized in 2003. This seems to be possible only if the necessary technologies were already available in 1996.

[5] In the list of the Top 50 topics there are two topics that we include in the problematic generalization category #6, which is not mentioned in the table. The panelists anticipated that the topic "Development of technology capable of forecasting the occurrence of major earthquakes (magnitude 7 or above), several days in advance" would be realized 2023. It seems that they had no idea of how to realize the target. Two topics, e.g., "Wide acceptance of LCA-style product design," had little to do with technological generalizations.

Table 1
Technological generalizations of the top 50 topics in the Sixth Japanese Survey [9]

No.	Generalization type	Example
1	From realized *technique(s)* to promising technique(s) Number of topics: 3 Average anticipated time of realization: 2009	Development of solar cells capable of maintaining 15% efficiency for at least 10 years without light convergence (ranking in importance 9, anticipated realization time 2010)
2	From realized *technique(s)* to promising target(s) Number of topics: 11 Average anticipated time of realization: 2007	Practical use of a highly secure next-generation Internet that allows the transmission of real-time information, leading to the implementation of Internet-based telephone services and motion video broadcasts (ranking in importance 8, anticipated realization time 2003)
3	From realized *target(s)* to promising technique(s) Number of topics: 3 Average anticipated time of realization: 2009	Establishment and practical use of plastic-recycling technology (ranking in importance 17, anticipated realization time 2007)
4	From promising *target(s)* to promising technique(s) Number of topics: 7 Average anticipated time of realization: 2012	Widespread use of nonfossil energy sources (wind, geothermal, solar [photovoltaic/solar thermal] and waste heat) in all areas of life including household, industry and transportation (ranking in importance 1, anticipated realization time 2018)
5	From promising *technique(s)* to promising target(s) Number of topics: 22 Average anticipated time of realization: 2014	Practical use of VLSI with as much as 256 Gbits of memory per chip (ranking in importance 2, anticipated realization time 2014)

In 1996 many plastic-recycling technologies were already available. What was forecast for this topic were more efficient and economic technologies. Widespread use of nonfossil energy sources is very much based on social choices, e.g., on energy taxes. When there are favorable social conditions, technologies based on wind, geothermal, or solar energy will become more promising. In 1996, there were available only weak scientific/technical signals about how to realize VLSI with as much as 256 Gbits of memory per chip.

4. Leitbilder of nanotechnology as sources of technological generalizations

What is the connection between different types of technological generalizations and leitbilder? Let us look at the leitbilder of nanotechnology. The term nanotechnology was coined in the 1970s in Japan and there is associated with Taniguchi and top-down miniaturization, "which can be regarded as the latest stage in mechanical engineering, which has pursued ever tighter precision of manufacture and tolerances throughout its history." [15]. In the 1980s, Drexler began to use the term nanotechnology to denote his vision of molecular manufacturing [16].

According to Grupp, "nanotechnology will have a key position in the technological development of 1990s and in the first decades of the twenty-first century."[17]. He describes the field as an enabling technology that "makes possible engineering at the level of atoms and molecules," and continues:

> This new basic technology can stimulate future innovation processes and new generations of technologies. It is based on the interaction of information technology, polymer research, optics, biochemistry and medicine and micromechanics.

Grupp's characterization of nanotechnology indicates the early-stage character of the field, but also shows the potential it holds. His description also underlines the interdisciplinary and cross-boundary nature of the area, which provides a substantial challenge to what is perceived as necessary collaboration between sectors and disciplines. Considerable efforts from various sides have been undertaken to forecast the development of this novel field of science and technology. For instance, the German Mini-Delphi study chose nanotechnology as an explicit category. Nanotechnology-related visions of the Delphi II study have also been compiled.

As we pointed out earlier, an emerging technological paradigm is typically viewed as a system of many, competing leitbilder (leitbild system). In the paradigmatic stage, an individual leitbild often begins to dominate, but not necessarily. A leitbild system is also characterized by a number of artifacts, techniques, etc. focused at a similar direction.

Table 2 contains a number of Delphi topics that can be used as examples of different leitbilder of nanotechnology. The forecasted realization times of the topics are inside a time horizon of 25 years. If the anticipated realization time of a topic is outside this horizon, it often is based on problematic generalization #6 in Fig. 1.

4.1. Leitbild 1

The first leitbild is related to nanoresolution analytical methods (Topics 20, 22). The leitbild here is to further improve existing tools by adding new functions to analysis tools. It can be seen as an example of the generalization activity #1 in Fig. 1. The development of analytical tools and techniques is closely related to progress in other areas.

> Often nano-resolution tools are identified with nano-resolution optical microscopy since these methods combine the possibility of measurement with that of manipulation, which makes them more versatile as tools for nanotechnology. A number of scanning probe microscopes have been developed and some of these methods do not require complicated sample preparation; e.g. the ability to work on in vivo substrates and determine structure–function

> relationships is the main reason why the AFM, the atomic force microscope, is the popular amongst biologists. It is said that even (nearly) two decades after its invention, the impact of the scanning-tunneling microscope and its follow-ups is still growing. In conjunction with continuous technical further development of this method, researchers are discovering new phenomena in the fields of physics, chemistry, and biology. At the same time the SXM methods are used as a nano-tool rather than a nano-probe. The idea is to modify surfaces and tailor their structures on the nano-scale, down to the manipulation of individual atoms. [18].

This case has shown that realized techniques—such as AFM and STM—can provide a basis for developing more sophisticated 'promising' techniques that will go beyond the mere measurement. Ultimately, they might facilitate large-scale manipulation at the nanometer level. However, this transcends the possibility horizon of Type #1 generalization activities (see Leitbild 5 below).

Table 2
Nanotechnology topics in the German 1995 Mini-Delphi study

Section "Cognitive Systems, Artificial Intelligence and Nanotechnology, Microsystems Technology," Subsection 'Nanotechnology'	Period of realization
14. Functional materials and/or semiconductor components whose compositions and dotting densities vary from atomic layer to layer are widely used.	2006–2010
15. Electronic solid-state components that consist of 'super atoms' of artificially composed atoms will be developed.	2006–2010
16. Methods to synthesize substances with new functions (e.g., polymer crystals with weak bonds) will be developed by way of combining various types of bonds at the atomic level.	2006–2010
17. Nanostructured materials with predetermined properties will be manufactured.	2001–2005
18. Organic hybrid composite materials that are based on the control of monomolecular layers will be developed.	2006–2010
19. Organic–inorganic composite materials will be developed (e.g., biomimetically) whose elements are at the level between several and a few dozen nanometers.	2001–2010
20. An analytical method that sorts out a particular type of atoms using high-definition surface-analysis techniques will be in practical use.	2001–2005
21. 'Atomic function elements' (atomic switches, atom relay transistor, etc., in which movements of a small number of atoms cause logical and/or storage functions) will be in practical use and have a higher reliability and processing velocity than solid-state components.	2011–2015
22. Reaction and synthesis methods at individual atoms or molecules of, respectively, atomic or molecular level of magnitude will be in use applying techniques from scanning tunneling microscopy.	2006–2010
23. Techniques to fabricate structures at the atomic level that will not be based on probing methods as represented by the scanning probe method will be in practical use.	2006–2010
B. Organic, molecular composed materials will be developed using the natural method of self-organization	2006–2010

Source: "Delphi-Bericht 1995 zur Entwicklung von Wissenschaft und Technik-Mini-Delphi." BMBF, Bonn, 1996, our translation.

4.2. Leitbild 2

Another leitbild based on Type #1 generalization activities is related thin layers (Topics 14, 18). Here, efforts appear to be directed at characterizing these structures.

> Thin-film technologies constitute a considerably well-developed field. An exact ultra-fine production of thin films is a necessary condition for the subsequent characterization. Designing ultra-thin layers can be associated with a small number of technical aims, such as atomically exact delineations of layers, quantumized potential distribution, defined pore distribution in layers, ultra-thin separation and protection layers, improved layer function by way of multilayer structuring. These technical targets are related to a greater number of applications. Examples are information storage layers, films with quantum effects, optical layers, multilayer piles for quantum/semiconductor laser and X-ray optical compounds, displays, sensor layers, tribologic films, biocompatible films, photovoltaic films, membrane films, and chemically active surfaces [20].

4.3. Leitbild 3

The third leitbild ranges around the notion of nanostructured materials. Nanomaterials can be seen as structures that have particular properties owing to their size. The leitbild in this context is to manufacture a nanomaterial in a way that allows predetermination of its properties. It can be seen as a generalization of Type #2. This generalization pattern describes the transition from realized techniques to promising targets. Paired with a better scientific understanding of the subject matter, a variety of already realized techniques allow us to develop rather concrete ideas of improved materials. The idea here is to take advantage of nanoscale characteristics of structures and substances to create new materials with enhanced properties, such as those common to polymers, composites, or other materials (Topics 16, 17, 19). The aim is not necessarily direct control of individual atoms; bulk operations suffice to exploit the nanoscale properties.

> One example to illustrate the idea of bulk-processing nano-materials is that of colloidal dispersions [19]. Colloidal science deals with the physics and chemistry of finely dispersed matter. Colloids are generally understood as particles or other objects with at least one dimension roughly in the submicron range. Nano-particles then are viewed as colloids smaller than 100 nanometer[s]. It is pointed out that colloid science has a long tradition involving nano-particles and that not all that is nano is necessarily new [19]. In this sense, colloids encompass gold colloids, colloidal silica, and aluminum oxide powders. Due to their small dimensions, colloids exhibit Brownian Motion. Owing to their large surface area, surface forces, such as Van der Waals attractions, and repulsions, due to the particle charge, determine the interaction between colloidal particles in the liquid phase. The balance between these forces critically depends on the details of the particle surface and the liquid composition. Colloids easily aggregate to form large flocs, networks or gels. The control and understanding of these aggregation processes is the major challenge of colloidal nano-science. Suspensions of colloids, or dispersions, are e.g. milk, blood, cosmetics, such as toothpaste, or ink. Examples for inorganic colloids are clay particles, iron oxides on computer disks and in magnetic fluids, pigments in paints, or powders for technical ceramics.

> Colloidal systems are studied from a (bulk) chemical synthesis perspective. Such research integrates the study of physical properties of dispersions and gelation phenomena, obtaining important input from computer simulations and statistical mechanics. It is said that this wide scope of colloidal science is unavoidable, since finely dispersed matter can be encountered in many disciplines and applications.

The nanomaterials leitbild provides a focus point for integrating this and other bulk chemistry topics with related activities.

4.4. Leitbild 4

While the preceding leitbild is to be positioned in the field of top-down nanotechnology, the subsequent leitbild addresses the nanoscale from a different, 'bottom-up' perspective. This perspective attempts to simulate nature to develop materials with novel properties by way of self-organization. These approaches are often dubbed 'biomimetics' (Topics 19, B).

> Brownian motion in a fluid brings molecules together in various positions and orientations. Given that molecules have suitable complementary surfaces, they can bind, assembling to form a specific structure.[6] The biomimetic approach can also be used as a path to obtaining novel materials, using self-assembly techniques to make organic templates on which inorganic structures are then deposited [15].

In this case, an integration of various techniques is necessary. It has been shown that one can create structures by way of self-organization in a biomimetic process. However, our technological means are inadequate to fully utilize the potential this leitbild offers us. Being aware of the general feasibility—thanks to already realized artifacts—we can make reasonable assumptions about the requirements of the techniques necessary to pursue this path of development further. This can be viewed as a generalization activity of Type #3.

4.5. Leitbild 5

This leitbild focuses on direct control of atoms, to rearrange them into new atomic structures (Topic 15). This could lead to novel materials. The difference between the materials approach mentioned above and this one is related to how one controls the process (bulk reactions vs. atomic control). Atomic control is also strongly related to the idea of atoms being effectively used as carriers of certain functions, such as data storage, etc.

> This idea is often associated with the notion of molecular nanotechnology. Contrary to the general usage of nanotechnology, which is related to other leitbilds, such as thin films, fine particles, chemical synthesis, advanced microlithography, etc., this approach is associated with a technology that is based on the ability to build structures to complex, atomic specifications

[6] See K. Eric Drexler, Nanosystems: Molecular machinery, manufacturing, and computation. New York: Wiley, 520. Drexler rightly points out that one should not refer to this as self-assembly but rather label it Brownian assembly. Self-assembly is a paradoxical name: How can a structure assemble itself or do anything, when it does not yet exist? (Question raised by Eric Drexler, op. cit.)

> by means of mechanosynthesis. Mechanosynthesis can be understood as chemical synthesis that is controlled by mechanical systems operating with atomic-scale precision, which facilitates direct positional selection of reaction sites. Molecular manipulators and mill systems are envisaged as suitable mechanical systems. Atomic force microscopes are seen as an early basis for these systems [21].

This leitbild follows a generalization pattern of Type #5. There are available only weak scientific signals in favor of it. Building on Type #1 generalization activities, it is based on the availability of eventually promising techniques and projects from envisaged techniques to promising targets. As pointed out in leitbild 1, we can reasonably expect current STM and AFM technologies to be further developed to more complex tools that open up fields that lie beyond measurement and observation of nanoscale structures and phenomena. One can assume that these tools will be used to manipulate structures at the nanometer scale. This enables us to generalize further from this sort of promising technique and make the step to improved and novel artifacts that result from nanometer-precise control of structures.

All five different approaches that we call leitbilds belong to one greater whole that eventually will develop into a technological system. As the exact shape of that technological system is unclear, currently, we speak of a leitbild system instead. One element of this leitbild system might even substitute and outdate another leitbild in the same system. For instance, what we identified as Leitbild 5 could one day replace Leitbild 3. Even though both approaches refer to nanostructures, they are essentially different. While Leitbild 3 uses bulk methods, Leitbild 5 aims at direct atomic control.

5. Conclusions

What is the contribution of our paper for the ongoing foresight processes, especially for the national technology foresight processes and the Millennium Project? The analysis of leitbilder and technological generalizations might contribute to the construction of topics and issues and to the argumentation processes based on them. We consider that expert panels constructing topics should firstly try to identify all relevant leitbilder in the field. There might be also relevant negative leitbilder based on dangers of emerging technologies. A useful further step would be to identify key actors representing the leitbilder found, both enthusiasts and critics. They are promising candidates for the expert panel of a Delphi survey. Enthusiasts might be good choices for making proposals concerning new issues or topics if they are able to sustain the basic comments of critics.

A difference between most national foresight studies and the Millennium Project is that the latter has resulted in the production of factual arguments concerning the nodes of discussion. For example, 15 Global Issues and 15 Global Opportunities were merged into 15 Global Challenges in the Millennium Project. Arguments concerning Challenges were discussed in the new kinds of discussion nodes called Actions [3]. We suggest that in technology foresight studies representatives of different leitbilder should be used to produce factual arguments. Experts representing different leitbilder would inform what they consider key successes or failures (realized techniques/achieved targets) in their field and how these successes or failures might function as starting points of promising technological generalizations or topics.

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Chapter in edited book. Ludlow. J.: Delphi Inquiries and Knowledge Utilization, in *The Delphi Method: Techniques and Applications.* H. A. Linstone and M. Turoff, eds., Addison-Wesley, Reading, MA, 1975.

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