A Perspective on GIS Technology in the Nineties

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ABSTRACT: Information technology is a rapidly changing field and its innovative ideas and accomplishments will affect the design and use of future geographic information systems (GIS). In order to make some predictions about GIS technology for the remainder of this decade, it is necessary to assess the development of new technology. Experience shows that the development rate of new computer hardware tends to be underestimated; however, expectations about improved software systems are usually higher than what industry can deliver. Considering these circumstances, possible changes in GIS technology and its use are assessed. The most important problems are shown to lie with the ability of organizations to adapt to new technology. The general challenge is to make the most effective and efficient use of new technology. Specific challenges from the user perspective are addressed in three areas: data quality and how it is communicated to the user, user interfaces designed from the user perspective, and cost-benefit analysis of geographic information. They point to current research that is expected to influence the GIS community toward the end of the decade.

INTRODUCTION

WITHIN THE LAST DECADE, geographic information systems (GIS) have matured from an attractive idea to an entire industry. This development can be observed in the market, in companies, academia, and the professions related to geographic information. Some idicators are

- The number of system installations has been reported to double every 2 to 3 years;
- The annual growth rate of the GIS market is estimated to be around 35 percent;
- Sales figures of some GIS vendors are growing at rates of 100 percent and more;
- A rapidly increasing number of regional, national, and international conferences are focusing on GIS, some on technological advancements and the theoretical foundation of GIS, some on applications of GIS for specific domains;
- A growing number of professional journals are publishing articles on geographic information systems, some of them adopting the terms GIS or LIS into their titles;
- A multitude of disciplines -- geography, engineering, forestry, computer science -- now emphasize GIS;
- Many universities are adding GIS courses and witnessing an increase of students' interests in GIS; and
- Finally, national research centers for geographic information have been established in the U.S. (Abler, 1987; NCGIA, 1989) and in Britain (Maher, 1990).

Spatial information technology has left its infancy and has become an established industry. The issue is no longer whether or not to use a GIS, but how to use it for the highest benefits. Public agencies and private companies are regularly using GIS technology, and they do so much more successfully than just a few years ago. The packages vendors now offer have breathtaking capabilities, with large arrays of functionality and sophisticated color graphics. Many applications are now operational and highly productive. Spatial information is rapidly becoming an essential factor in all kinds of decision making tasks. GIS products furnish the required information at the right time, leading to better informed decision makers (Armstrong and Densham, 1990).

This paper attempts to analyze the current situation and predict some trends for the future. Development of radically new technologies is slow. It takes years for a new method to be introduced, tested, and adopted for operational use. From past examples, we conclude that the development and market introduction of a new idea in GIS takes about 8 to 10 years; therefore, we conclude that all the technology that will affect the utilization of GISs in this decade must be already in a research or development laboratory. To predict the future in GIS, one must assess the current research work.

Predictions are necessarily subjective assessments, based on the understanding of the technology, the field today, and one's experiences. We do not expect that others will agree fully with our views, but we hope to stimulate and encourage the publication of other opinions on this subject (Dangermond, 1991).

The remainder of this paper assesses the past development of hardware, software, data, and institutions involved in spatial data processing. We try, then, to predict quantitative and qualitative changes in the future of GIS. Impacts on prospective users are discussed from three different perspectives: data quality, user interfaces, and cost-benefit analysis of GIS.

TECHNOLOGICAL EVOLUTION

It is beneficial to examine, at the outset, the development of the different components of a GIS, as well as their roles. There are four major parts of a GIS:

- the *institution* using the information system: people, their management, methods, and connections between organizations;
- the *data* describing some part of reality and stored in the information system;
- the *software* used to manage and analyze the data and derive the desired information; and
- the *hardware* used to store, process, and present data.

The order of the components listed here implies their significance, beginning with the organization and people who actually use or are served by the system, and ending with the tools necessary to produce the desired information. The following discussion progresses "bottom-up," i.e., from the less important hardware considerations to the most crucial institutional aspects. It seems necessary to deal first with the rapid development of hardware which attracts enormous attention and appears to drive the GIS technology. We will demonstrate, however, that such rapid development is translated into practical use at a much slower pace.

HARDWARE

New hardware is being developed and introduced at very high speed (Faust *et al.*, 1991). The trends commonly observed include

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- processor speed doubles every year,
- memory capacity — both primary and secondary — grows at a similar pace, and
- the physical sizes of whole systems shrink.

A decade ago, computers needed dedicated, air-conditioned environments and specialists to operate them. Now, one can have a Personal Computer or a Workstation sitting on an office desk, and it is many times faster than the older mainframes. There are no indications that the speed of this development will decrease in this decade. Even though there are ultimately physical laws that will limit speed and miniaturization, such as the speed of light and the need of at least one electron to store one bit of data, these limits are far beyond current technology.

Today, hardware for GIS involves more than stand-alone machines. Workstations are linked by local area networks in order to share processing, and to access common database servers and peripherals. *Interoperability*, i.e., access to hardware and software from several vendors in the same network, is emerging as a requirement for large GIS applications. Several network clusters at multiple sites can be connected by telecommunication links across states and continents to form wide area networks.

It should be noted that not everything mentioned in trade journals is actually availabe. From the announcement of a new product to its use by a small, advanced user group, more than a year may pass. It may take up to two or three years until a product penetrates the U.S. market. Even if a product is available, it may be far from usable. New products are often incompletely developed and expensive to acquire because they require considerable time and effort before they can be used productively.

Software

Software development is expensive and time consuming. Unlike the development of new hardware, the production of complex software systems is still a major problem. The growing gap between improvements in hardware and software, the so-called *software crisis* (Traub, 1989), has been widely discussed during the last decades. No easy solutions have appeared so far. Despite the wide-spread application of software engineering methods, the cost of software has dramatically risen without a similar improvement in its quality. A study of software produced for the Department of Defense (DoD) in the U.S. revealed that only 10 percent of the software systems could be used as delivered, and over 50 percent were never used at all — even after costly revisions (Buckely and Poston, 1984). Several major software developments in GIS in the last years were introduced into the market years later than planned and with a cost much higher than expected.

What are the reasons for such poor "performance?" Innovative accomplishments in software engineering have been rare. Despite tremendous research efforts, attractive new ideas such as parallel programming are not yet ready for commercial use. Consequently, most of the concepts and ideas used today are quite dated:

- The *programming languages* currently used in industry, such as COBOL and FORTRAN, are almost 35 years old. The popular "new" languages, such as Pascal and C, have been around for 20 years and are slowly taking over. ADA, developed as the language of the future 10 years ago, has found little popularity outside of DoD contractors.
- A similar observation can be made for *operating systems*. Those in use today (e.g., VMS, MS-DOS, UNIX) were developed 10 or 20 years ago and the motivations for many of the solutions have long vanished with the rapid development of new hardware. Two examples. The cryptic short commands of UNIX were invented to reduce typing at a time when painfully slow teletypes were the common input device. The 640 Kilobytes boundary that limits programs under MS-DOS is testimony for a time when 128 Kilobytes was considered a very large memory capacity and more than a single user could afford — at today's price, 128 Kilobytes is less than $10.
- Today's most popular *Database Management Systems* (DBMS) employ the relational data model which was developed 20 years ago primarily for business data (Codd, 1970; Codd, 1982). Their support for the complex data types, relationships, and integrity constraints in large collections of spatial data is insufficient, conceptually as well as in terms of efficiency (Frank, 1988).

Compared with the fast-paced hardware production environments, today's software engineering environments are antiquated. They result in programs which are always "almost" finished and will appear "REAL SOON NOW" — which can be translated to mean that the development is behind schedule and there is no idea when the product will be finished. When finally received — after much delay — the products often lack a usable manual and have many "bugs" (Brooks, 1972).

GIS software often looks flawless during a demonstration, and prospective users may be lead to believe that it will perform exactly the jobs expected. Impressed by hardware performance and nice pictures on the screens, it is hard to see the actual problems with *using* these systems. One tends to assume optimistically that adaptations will be easy or that the vendors will come out with new versions solving all the remaining problems. Unfortunately, this is usually not the case, because adaptations to the specific problems of an organization are sometimes very difficult; system performance may be much slower when working with actual data sets and not the tiny demonstration examples; and the integration of work performed by different persons in a team may be very difficult.

Data

The economic life cycle of hardware is currently about 3 to 5 years and software systems are used for 7 to 15 years. Data managed and processed by such systems persist for a much longer time. In a GIS, data may be kept unchanged for several decades. An example is data describing land parcels in a rural area. Land ownership changes approximately every 7 to 10 years in the U.S. and the geometric description of parcels is even more stable (Jeffress, 1991).

Apart from the potential long-term value of spatial information, the *cost* for collecting spatial data and keeping the collections up to date is enormous. Over the lifetime of a GIS, we estimate that the ratio among the cost for hardware, software, and data is approximately 1:10:100. In order to reduce the cost of GIS solutions, one should concentrate on improving data collection and maintenance procedures — even if more hardware components or software modifications are necessary.

Another increasingly important aspect of data is their *multiple use*, within an organization and across institutional boundaries. Due to the high cost of data collection and maintenance, data need to be shared among users and integrated with other data collections. Spatial data in digital form are becoming generally available, e.g. TIGER files (Marx, 1990), Digital Line Graph data (Cowen *et al.*, 1990), and satellite imagery, and standard data exchange formats have been defined (NCDCDS, 1988). Thus, the technology for data sharing is rapidly developing. The crux of data exchange and data integration, however, lies in conveying the meaning of the data and to communicate the quality of the data exchanged (Chrisman, 1983; Robinson and Frank, 1985). To describe spatial data so that a receiver can extract useful information from them remains a major problem. It is insufficient to transfer only the data files, because the receiving institution must exactly understand what is represented and what limitations the data collection has. If this is unclear, the receivers may use the data in an inappropriate manner (e.g., using topographic map data from a 1:25,000-scale map for detailed earthwork projects) and disastrous misinterpretations may follow, leading to liability law suits (Epstein, 1987). It has become technically feasible to exchange spatial data, but exchanging *spatial information* is another matter.

Institutions

Introducing a new technology into an organization requires that the organization adopt new methods for decision-making. Organizations are very difficult to change and they react very slowly and reluctantly to pressure for change.

Typically, in a *first phase*, an existing function of an organization will be automated such that an information system more or less completely and exactly replaces previously manual tasks. While this causes least disruption, it also makes the least use of the potential of the new technology. It carries forward all the constraints imposed by the previous technology to which the organization had adapted over the years; in this case, all the restrictions of spatial data collection, storage, presentation, and distribution using manual cartography. Many of the current GISs show their roots in systems to maintain a collection of maps. They divide reality into "map sheets" and are concerned with cartographic symbols, not real objects.

New technology should lead to systems which improve the quality of the work performed. For a GIS, this means that the availability, quality, and timeliness of spatial information for decision making should be improved compared to the manually produced information. In many cases, it also means that jobs can be done which were previously impossible or impractical. These are the desired, though not always achievable, effects which need not cause resistance within organizations.

It is surprising to observe that the development of new hardware creates so much excitement and receives so much attention in the public eye — at least in the technology oriented societies of the anglo-american world — despite the fact that much of the new hardware is not really used. At best, it serves to replicate previously manual methods without fully realizing its potential. This is specifically true for the field of telecommunication and computer networks where the only widely used application is electronic mail which replicates the postal service. Surprisingly, really innovative applications of new applications are extremely rare and not widespread.

CHANGES IN INFORMATION TECHNOLOGY

The rapid development of hardware technology is both quantitative and qualitative. Certainly, we will see an increasing amount of computer equipment in offices, allowing us to perform traditional work faster. At the same time, this technology boost will allow us to develop new methods for solving old problems, and to investigate and solve new problems. What kind of changes should we expect?

Quantitative Changes

First, some estimations about the quantitative development within the next decade:

- Processing power will continue to grow fast. "Twice the speed of the year before" is a likely scenario to be repeated over the next few years and there are more optimistic predictions such as Joy's law that the CPU performance in million instructions per second (MIPS) is $2^{(year-1984)}$ (Stonebraker *et al.*, 1988).
- Prices for main memory will continue to decrease — about 50 percent bi-annually — and large amounts of main memory for each user will become economically feasible. While it makes current economic sense — based on the price ratios of processors, memory, and disk accesses — to make data, *referenced every 5 minutes*, memory resident, it is likely to increase to 5 hours within the next 20 years (Gray and Putzolu, 1987).
- The access time of hard disks will increase very slowly. At the same time, the capacity of hard disks will grow and price will decrease.
- Communication networks for the exchange of large data volumes will proliferate. This will happen at a slower pace than hardware development, because organizational and political issues are involved.

In the late 90s, we may see the following specifications for a personal GIS workstation:

- A CPU with 500 MIPS,
- 500 Megabytes of main memory,
- 5 Gigabytes of storage space on hard disks and an additional 50 Gigabytes on optical disk,
- a workstation screen with 2,000 by 2,000 pixels, and
- a communication device with 100 Megabits per second transfer rate.

We expect that a workstation with these capabilities will cost about the same as today's personal computers having 2 to 5 MIPS CPU performance, 4 MB main memory, a 100 MB hard disk, 600 by 900 pixels screen, and a 10 Megabits per second Ethernet adapter.

Qualitative Changes

The rapid increases in hardware speed and capacity allow spatial analysis and other work to be done more quickly, but will also affect the way things are done. Our biggest challenge will be to understand how to use this new potential to the best advantage.

Turning around the quantitative development of the hardware into products has proven to be difficult. Particularly, the increase in complexity in the software systems desired will more than offset the increase in programmer productivity. Thus, software will remain the crucial factor limiting further development. Construction of software will become exclusively the domain of the software engineer, and GIS users, programming in a base programming language, will become a scenario of the past. One of a kind, special systems will become extremely expensive and the trend toward the use of off-the-shelf systems will continue. Adaptation of systems to organizations will become extensive and very high level, specialized languages — sometimes called macro language — to tailor systems to specific needs will be widely used, forming the base of a sizeable consulting business.

DBMSs will be used for all the data, and computer networks will become prevalent. It remains unclear to what degree solutions for the integration of the team members and their contribution to an institution's task can be achieved. Research into *computer support for cooperative work* is in its infancy and only very limited example programs are on the market today. Two important technical problems need to be solved for GIS:

- *Long transactions*, i.e., when two or more changes, worked on by different users independently, interact because they affect the same data and each of these transactions takes days or months to complete (Garcia-Molina and Salem, 1987).
- *Versions*, i.e., when users need to be able to develop several independent alternatives for a planned development (Katz, 1990; Theriault *et al.*, 1991).

The ways in which computers are used will change not only due to their larger capacity and faster processing speed, but also due to their physical size and weight. Take the new notebook computers, weighing less than 7 pounds, as an example. They do not replace standard personal computers, but effectively replace notepads nad pencils during travel and meetings — with the additional benefit of access to personal databases, spreadsheet programs, and other data. Integrating these mobile machines with the stationary computer networks poses interesting problems such as keeping the databases up-to-date independent of the mobile machines which are not always

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connected to the network. Technical solutions are known, but logistics and software are not available.

One can easily predict that, in the near future, GIS functions will be implemented on machines which can be carried into the field; however, the availability of a technical system does not automatically assure its success. "GIS in the field" may be used, for instance, to access utility line plans, particularly when responding to emergency calls. Current work crews lack the qualification to operate a GIS. Should they be trained or, rather, should the GIS user interface be simplified? How will a small computer stand up in the harsh work environment? And how will it be secured against theft?

Rapid Changes in Technology as a Problem

New technology is constantly put on the market and at a growing pace, targeted to replace "old" technology. This increased turn-around frequency causes severe problems to the setup and maintenance of information systems in an organization that desires stability. Fast progress is the dream of many companies and societies — until they realize the problems associated with it:

- The *economic life cycle* of equipment is short, because new devices will soon appear to replace it. The market for used computers is volatile and prices paid for used equipment are depressed by the rapid appearance of new and cheaper models. Equipment bought last year for $100,000 may be worth less than $20,000 this year.
- *Maintenance* of a computer system has become a major economic factor. Frequently, computers must be replaced even though they are working satisfactorily, because costs for regular maintenance are higher than the costs of buying a new computer.
- Decisions to buy new hardware are difficult in the light of new models appearing on the market every 2 to 3 months. When does one decide to buy?
- The cost of introducing a new system is high. Conversions from one system to another are often not as simple as promised and therefore more expensive. Special problems are caused by the transfer of existing programs and data to the new system. Retraining efforts can be costly as well.

A GIS cannot follow all the small advances of the technology. There must be some stability; otherwise, users will be working on keeping up with changes from one version to another, rather than concentrating on solving actual problems. Thus, it is often necessary to continue with an established plan, even if it does not involve the absolutely newest technology. Planning should anticipate likely developments, but hardware decisions should never be fixed earlier than absolutely necessary. This means, in practice, that one starts the acquisition process with a functional description and an indication of some existing product, adding "or the best available at the moment purchase" so that the decision on the specific product is delayed until the moment of the actual order. Otherwise, one may — after a lengthy process of purchase approval and financing — end up buying the product which was adequate two or three years ago, but completely out of date and too expensive now.

CHALLENGE FROM A USER'S PERSPECTIVE

Having discussed the challenges introduced by the fast pace of technology innovation, we want to change out point of view to a user's perspective. What innovations can be expected that will improve, not just the processing and storage capacity of GIS but their *usability*? GIS vendors are confronted today with the challenges that *what* a system can do counts less than *how effectively* the system can be introduced into an organization, learned, and used. We will discuss here three typical aspects of this usability issue: data quality, user interfaces, and cost-benefit analyses.

Data Quality

Data are never absolutely precise and spatial data are no exception. Spatial data describe location with a certain error; they may be out of date or the data collection may be incomplete. Humans automatically take into account a number of data quality aspects when using data in a decision process. For example, an expert would never base a map at 1:100 scale upon coordinates which were derived from a 1:100,000 scale-map. Likewise, rough sketches made in the field will not be "copied" onto a highly precise blueprint.

Technical drawing standards allow for the communication of information about data quality. With computers, however, the generation of drawings becomes much simpler so that an unskilled person may produce renderings of high graphical quality. Drawings can be easily scaled, and the results are always presented with the same graphical quality.

GISs have much more potential for data misuse than traditional drawings and maps, because their data presentations lack intuitive cues indicating data quality (Beard, 1989). This can create serious problems for users who have to be advised of the data quality and validity for their decision processes. It can also become a liability issue for the furnisher of data who may be held liable for damage resulting from using data for purposes never intended.

It will, therefore, be necessary to investigate the quality of data and its visualization. Humans intuitively handle information on data quality. These intuitive processes must be formalized so that they can be integrated into the software systems. Formal processes are needed that propagate indications on data quality and validity from source data to results. Visualization methods must be found to present these indications to the users in an effective, unobtrusive way. Research in this direction is under way (Beard *et al.*, 1991).

User Interfaces

For GIS users, the user interface *is* the system. The design of interfaces determines how effectively they can do their work. The user interface should hide internal details — how data are stored, composed, or decomposed — so that users are able to concentrate on their tasks.

Anyone who has ever tried to use a GIS will agree on how difficult it is to "learn" a system. Training usually takes a long time and is expensive. Experience with non-GIS applications demonstrated that visual interfaces based on direct manipulation, as popularized by the Apple Macintosh or the PC Presentation Manager, are easier to learn than traditional command language interfaces, and that user productivity increases at a faster rate.

Unfortunately, applying these user interface innovations to GIS is not straightforward, and progress is slower than expected. The problem of designing effective GIS user interfaces is not one of substituting typed commands by menus. It is rather a problem of finding out which concepts and operations a user executes and how these can be logically grouped so that learning them is easy and a smooth interaction can be achieved (Egenhofer, 1990).

The common opinion that the interface is "something to be done after the design and the implementation has been completed" is fatal. Such user interface designs are cosmetic enhancements which do not help to make a system "user friendly." The reverse process — designing the user interface first — is seldom pursued. GIS design has traditionally progressed bottom-up, with a focus on storing and accessing *n*-dimensional data. Inadequate attention has been paid to a user's view of GIS operations.

Current commerical GISs widely disregard fundamental aspects of human-computer interaction. GIS users need extensive and expensive training prior to using a particular system, due to the researchers' and designers' concentration on functionality and implementation rather than usability. Systems tend to evolve from a small set of commands to hundreds of features without the necessary considerations of how users learn them and interact with them. The closer the interaction between users and GIS approaches the communication about spatial problems among humans, the more natural it will appear and the less time will be necessary to "learn" it (Kuhn and Frank, 1991). Thus, user interface design requires more than the user of mice, windows, icons, and menus.

Improvements to GIS user interfaces in this decade can be expected from interdisciplinary efforts in computer science and cognitive psychology. The focus of these studies are humans and their ways of thinking about space. The goal is to match the concepts in user interfaces as closely as possible with those used by humans. GIS users should be able to express their needs using the concepts which are most natural to their tasks. They should not have to organize their thoughts as dictated by a computer system.

An additional problem, coming into focus now, is created by the cultural differences among GIS users. Most GIS software is produced in the U.S. for the U.S. market, with some contributions from Canada or Europe. Beyond the surface problem of translating manuals and commands — which is difficult enough — the overall adaption to underlying cultural differences is a major concern (Mark *et al.*, 1989). For example, there are linguistic differences in the structure of the description of spatial motion between Romance and Germanic languages. This and other differences may reveal how people think about space in different cultures. They obviously affect the construction of user interfaces, perhaps even some parts of the internal structure of a GIS.

Cost-Benefit Analysis

New technology should not be introduced unless it can be shown to be cost effective. To use modern technology for its own sake is quite unreasonable; however, showing cost effectiveness of an information system, and especially a GIS, is difficult.

It is usually possible to establish what the cost of the current system is, even if some hidden costs cannot be assessed. It is also possible to estimate the cost of a new system, taking into account not only the purchase of the system, but also the cost for maintenance, data acquisition, training, etc. Thus, assessing the cost of a system is feasible and may be sufficient to show that the new system is less expensive to run than the current one and will reduce overall cost (Dickinson and Calkins, 1988).

This is not, however, the full picture. A cost-benefit analysis has to compare the cost of a system with the benefits that it will produce. Even if an information system replaces an existing manual approach and can be justified on cost reduction alone (with constant benefits), additional benefits will be reaped. In nearly all cases known, unforeseen benefits were much more important than those projected.

GISs are capable of producing spatial information products in formats not currently possible but highly useful for decision making. They can provide actual decision support *in lieu* of producing large amounts of output with little relevance or focus to the problem at hand. They can deliver this information closer to where it is needed and can react faster and more specifically to information demands. As a result of the introduction of a GIS, the response of an agency or organization to the needs of its clients may improve greatly, sometimes at reduced cost.

The difficulty is to predict these opportunities for new information products, given that the current users of the system are not always aware of them. Even if these innovations can be foreseen, a value — not a cost — has to be associated with them. Assessing the benefits of GIS innoviations — determining what has value for the users and their organizations — will be one of the major challenges in the Nineties.

Conclusions

A GIS should be understood as a complex system that is influenced by many factors. We have presented two aspects which we think are the most important ones today: (1) the push for development resulting from the rapid advances in the technology used and (2) the necessity to better understand and adapt to users and organizational needs.

The technology used in GISs changes very rapidly, creating both a challenge and an opportunity. It is a challenge to find the best ways of using this technology, not only to automate current operations, but to implement solutions which were not feasible before, and to develop new methods for solving old problems. It is an even greater challenge to work in an environment where most characteristics change rapidly and where it is not always possible to go with the "latest and newest." We pointed out that the speed of hardware development is usually underestimated — new capabilities come faster than we expect — and that expectations of what software can achieve are often too optimistic. Most of the software engineering technology is decades old and progress is much slower than anybody wishes. Software is often delivered late, with less functionality than expected, over cost, and with "bugs."

On the other hand, we have stressed that GIS developments must not be pushed by what technology makes possible, but by understanding what society needs and how it can benefit from GIS. We have addressed three subtopics in this area and tried to argue that

- GIS must appraise users of the quality of the information products so that users are not mislead. This is an issue of fairness. It affects usability and may become a major liability problem for the supplier of spatial data.
- User interfaces with GIS must become easier to learn and use. They should be designed from the user's perspective and not reflect the internal implementation decisions. Interfaces must be adaptable to different levels of user expertise and to other languages and cultures.
- Methods to assess the benefits must be added to those determining the cost of GIS, in order to demonstrate the effectiveness of GIS solutions. Experience shows that GISs tend to produce more benefits than expected, but there are not easy ways to predict and assess these.

GISs should be understood as systems in a wider social and economical context. GIS technology has to provide a useful service to an organization and to society at large. To achieve this, it is important to realize that the key problem is not technology as such, but its faster rate of change. Thus, instead of worrying about today's new gadgets, we should think about how to cope with the rapid evolution towards tomorrow's technology.

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