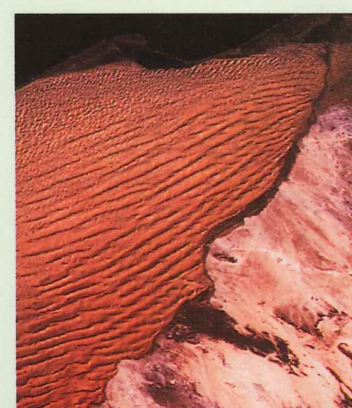
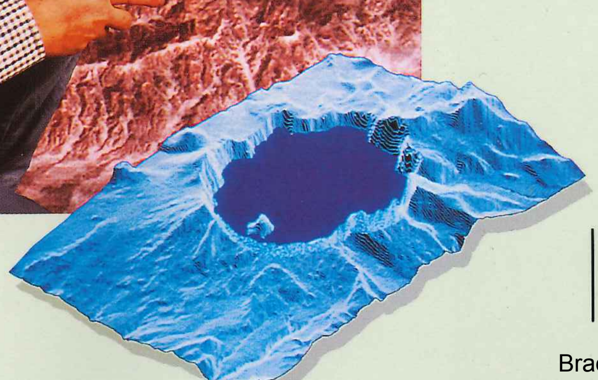
GEOGRAPHICAL INFORMATION SYSTEMS

VOLUME 2 : APPLICATIONS

EDITED BY
DAVID J MAGUIRE,
MICHAEL F GOODCHILD
AND
DAVID W RHIND





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GEOGRAPHICAL INFORMATION SYSTEMS

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PRINCIPLES AND APPLICATIONS

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Dedicated to the memory of

DAVID S SIMONETT

1926–90

David Simonett was born in Australia in 1926. After earning a Doctorate at the University of Sydney, he became a leading pioneer in the field of Remote Sensing, holding faculty positions at the University of Kansas, the University of Sydney and the University of California, Santa Barbara. He was director of land use applications at Earth Satellite Corp from 1972 to 1975.

As Chair at Santa Barbara from 1975, he was able to build one of the foremost Geography programs in the US, culminating in 1988 with the establishment of the National Center for Geographic Information and Analysis. The Santa Barbara site of the Center was renamed the David Simonett Center for Spatial Analysis in 1990 in recognition of his role in its creation. He received the Honours Award from the Association of American Geographers and the Victoria Medal from the Royal Geographical Society.

David Simonett lost a courageous fight against cancer on December 22, 1990 in the course of the preparation of his contribution to this book. The editors dedicate this book to his memory and to the outstanding role he has played in the development of the field of Geographical Information Systems.

(a) Nature of spatial data

(b) Digital representation

CAR NAVIGATION SYSTEMS

M WHITE

Automobile navigation is a demanding application of digital maps and appears likely to become a common and economically important one. A few systems are commercially available and many prototypes exist. These systems determine location using wheel rotation sensors, solid state compasses, inertial devices (gyros and other novel devices), radio location or some combination of them. Requirements of the source maps depend on the methods used and the user interface, as well as on functions performed in addition to location determination (such as map display, verbal directions, pathfinding and destination finding by address or landmark). Typical map requirements for particular systems include positional accuracy to the order of a car length, detailed street classification, turn restriction data and topological encoding. Creating such digital maps to support navigation is a daunting task. At the time of writing, there are several pilot projects, just a few commercial operations and some fledgling consortia which have as their mission the production of digital maps for navigation or the promulgation of standards for such maps. All systems require faster retrieval than GIS systems have typically provided. Applications using navigation systems include experimental traffic systems, such as traffic congestion reporting and 'sign-post' transmitters and receivers for communicating with on-board navigation systems.

INTRODUCTION

The automobile is becoming a much richer electronic environment for the driver. On-board computers, cellular telephones and vehicle navigation are already available, and real-time traffic information and route guidance have been demonstrated. The market for factory-installed systems appears to be huge. In Japan, Nissan has been selling more than 1000 systems per month as an option on the Nissan Cedric. This option is a combination of navigation system and television (which can only be operated with the vehicle stopped). In Germany, Bosch began to sell the Travelpilot in 1989. In the United States, Etak sold 2000 Navigators over a period of two years. Because electronics are pervading the automobile, a factory-installed navigation option will probably become inexpensive, perhaps less than US $500. As a consequence, demand for and use of digital map data will grow. Market analysts have estimated that sales of navigation systems will grow from US $5 million in 1990 to US $100 million in 1994 (Frost & Sullivan 1989).

Car navigation uses maps intensively. The map must provide information for:

- determining and maintaining the location of the vehicle in relation to features represented on the map;
- displaying a map graphically or generating routing instructions in text or voice;
- linking effectively with infrastructure.

This chapter reviews the current 'state of the art' of digital mapping as regards vehicle navigation and, since it is still in its infancy, some speculations are made about likely future developments. The infancy of the technology is reflected in the meagre

Fig. 43.2 The Honda Gyrocator screen (courtesy author).

supply of prior research considering the subject and directly related cartography (Petchenik 1989). Marine navigation is not included in this discussion. It has similar requirements and applications and, indeed, was the origin and inspiration for much of the current vehicle navigation technology. However, it differs in many ways from land-based vehicle navigation and warrants separate discussion.

The following sections discuss vehicle navigation systems and methods already in use and how information is displayed graphically, reported textually or by voice. Then applications such as finding destinations and pathfinding are considered. Finally, there is a review of the essential characteristics of digital maps, in so far as navigation and its related functions are concerned. From this, it will become evident that navigation and related applications require a topologically encoded and seamless database, as well as very fast data retrieval.

NAVIGATION

There are only a few vehicle navigation systems commercially available at the time of writing (mid-1990). In the United States, the Etak Navigator has been available since 1985. The Bosch Travelpilot, a derivative of the Etak Navigator, became available in Germany in 1989. Both of these systems are 'after-market' devices, that is, they are installed after manufacture and usually after the end-user purchases the vehicle. In Japan, the Toyota Crown and the Nissan Cedric have offered factory-installed navigation options since 1987 and 1989 respectively. The Etak, Bosch and Nissan systems use dead reckoning and map matching (explained below) but the Toyota system uses only dead reckoning. The map matching systems require topologically encoded digital maps, whereas the Toyota system uses bit-mapped images of paper maps (see Plate 43.1 and Figs. 43.1 and 43.2)

Fig. 43.1 The Nissan Cedric screen (courtesy author).

In addition, there are several experimental systems and 'concept cars' either demonstrating or 'mocking up' navigation systems. In an auto show in Japan in early 1990, more than a dozen

Fig. 43.3 The Autoguide screen (courtesy Department of Transport).

manufacturers showed such concept cars. This indicates a strong interest in navigation and, by implication, maps for navigation. Examples of experimental systems include the Philips CARIN (Thoone 1987), Clarion NAVI and the UK Autoguide (Catling and Belcher 1989). CARIN and Autoguide present stylized graphic instructions representing the upcoming intersection to the driver (see Fig. 43.3). Only the general principles on which such systems work are known: all the current vendors of navigation systems regard their software and data storage methodology as proprietary and, accordingly, do not reveal details. This is unsurprising because navigation has pushed forward the frontier of map access technology: typically, on-board computers are much less powerful computationally and contain less copious RAM than 'normal' GIS require and, at the same time, demand a faster response rate than available GIS offer. In addition, navigation algorithms and their implementation have involved substantial expenditure. The commercial stakes are high and, accordingly, secrecy prevails on the internal details of each vendor's offerings.

POSITION DETERMINATION

Navigation includes determination of position as well as guidance toward a destination. There are three essentially different technologies used for position determination. These are dead reckoning, radio location and proximity beacon detection. They can be used alone or in combination. Destination finding and guidance towards the destination have various quite different user interfaces.

Dead reckoning and radio location

Dead Reckoning (DR) is the process of computing an updated position from three inputs: details of a prior position; the distance travelled from the prior position; and the heading travelled since that prior position. The Etak Navigator, Bosch Travelpilot and Nissan Cedric all use DR. Figure 43.4 illustrates dead reckoning. To measure the distance travelled, all three use sensors mounted on the wheels. Other systems have tried to use the vehicle's odometer but this is much less accurate.

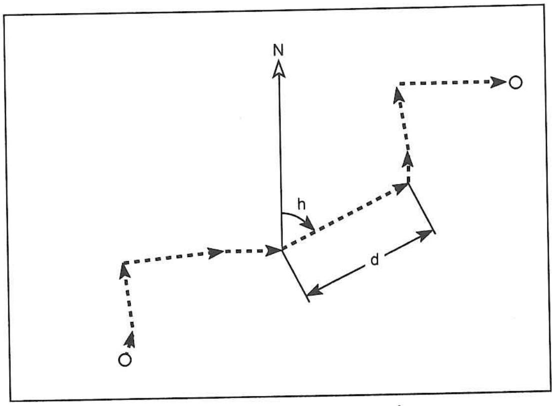

Fig. 43.4 Dead reckoning – computing a new position from heading (h) and distance (d).

For determining the heading, two measurements are taken. An absolute heading estimate is made using a solid-state compass (e.g. see Phillips 1987) and a relative heading is computed from the wheel sensor measurements. A solid state compass (i.e. a two-axis magnetometer) measures two components of the ambient magnetic field; from this the horizontal component of the earth's magnetic field is computed. There are many physical considerations involved such as the magnetic flux focusing effect of the steel in the vehicle and the local magnetic declination. However, all mapping considerations eventually come down to using the approximate position of the vehicle, a model of the earth's magnetic field and the measured magnetic field. An important consideration for in-vehicle applications is dip angle, the angle that the plane of the compass makes with the earth's magnetic field vector. The earth's magnetic field is horizontal only at the magnetic equator, which coincides approximately with the geographical equator. So the compass measures the magnetic field vector projected on to its own plane. While this is normally close to horizontal, local variations in ground slope caused by hills and the road crown may amount to several degrees and affect the compass/magnetic field relationship accordingly. Computation of the heading from compass measurements must take all these effects into consideration.

The difference in the distance travelled on two opposing wheels depends on the change in heading. When travelling straight ahead (i.e. without heading change), the two wheels travel the same distance. When turning, the outside wheel travels further than does that on the inside of the curve. Thus wheel sensor readings yield relative heading information. Again many physical considerations come into play, including wheel base, circumference, radius of curvature of the turn, steering geometry and wheel slip. Taking all these factors into account, however, a new heading can be computed from the prior heading and the difference in distance travelled by the two wheels.

Other sensors are under development or have been demonstrated in experimental systems. These include a gyro turning rate sensor, a vibrating rod turning rate sensor, an inclinometer, a GPS (Global Positioning System) receiver, a LORAN-C receiver and an optical speed sensor.

A gyroscope (more commonly a 'gyro') is a spinning mass and the vehicle's turning rate is measured indirectly by measuring forces resulting from the conservation of momentum; such forces can be experienced by holding a spinning bicycle wheel off the ground and turning it. Large gyros are used in inertial navigation systems common on board ships or aircraft. The vibrating rod sensors also operate on conservation of momentum. An inclinometer measures the angle of inclination of a stationary (or, more generally, a non-accelerating) vehicle and may be used to remove the effects of dip angle on the compass measurement as well as effects of hills on distance travelled. Any acceleration experienced affects the inclinometer so this must also be considered. As a group, the gyro, vibrating rod and inclinometer are all inertial sensors: they depend on the physics of momentum and inertia for their operation. For a survey of such inertial navigation sensors, see Smith (1986).

GPS and LORAN-C are radio location systems. These radio location sensors are not used in dead reckoning. Instead they provide position 'fixes' that are independent of the prior position. They both operate by an on-board receiver and computer comparing signals from multiple transmitters and determining receiver location from known transmitter positions and signal propagation times. The LORAN-C transmitters are based on the ground and the GPS are on a constellation of satellites in orbit. GPS will cover the entire globe when the satellite constellation is completed. French (1986) provides an overview of radio location systems.

Compass and radio location sensors are 'absolute' sensors; in contrast, wheel sensors and gyros are 'relative' sensors. Relative sensors give change information and absolute sensors provide information with respect to the earth itself. All sensors, however, suffer characteristic defects. Wheel sensors and gyros have noise and bias. Magnetic compasses measure magnetic anomalies as well as the earth's magnetic field. Radio location (GPS and LORAN) signals are distorted or blocked in highly urbanized areas. Manifestly, the sensor characteristics are important in assessing the accuracy of the estimated position. In addition, however, combining sensors can yield good results even when one sensor is noisy or fails entirely. The Etak method of computing heading, using both a compass and differential wheel sensor measurement, is an example in which the absolute sensor (the compass) suffers no accumulation of error and the relative sensor (the differential odometer) is unaffected by magnetic anomalies – yielding a combined result that is rarely erroneous (Honey, Milnes and Zavoli 1988).

Despite such accurate and resilient methods of deriving heading, the accuracy of a dead reckoned position still also depends on the accuracy of location of the prior position. The ineluctable errors in sensors lead to accumulated error in DR position. In practice, DR alone is insufficient for navigation since the accumulated error will eventually exceed a threshold of usefulness. So occasional fixes are needed, achieved either by human intervention, radio location or map matching. The first of these is tiresome and assumes accuracy on the part of the user; the third method is discussed in detail below. Radio location, however, has characteristic errors that are quite different to those already discussed. These errors do not accumulate over time or distance. Instead, signals are typically received clearly and the error level is the characteristic minimum or, alternatively, there is no position information available. It is, however, possible to dead reckon between radio fixes or, as Etak has done, use radio location (in this case LORAN-C) as just another sensor to be considered in location determination.

Map matching

Map matching is used to remove accumulated error from dead reckoning. The path travelled is determined by dead reckoning or radio location and integrating this with roads and intersections constitutes map matching (see Fig. 43.5). Dead reckoning with map matching is like navigation with absolute sensors in that the error in estimated position does not continue to grow (as it does with use of dead reckoning alone). It differs in that, once lost, the map matching algorithm is unlikely to recover; absolute sensors, on the other hand, may fail for a time or region but, outside that period or region, they have their usual error characteristics.

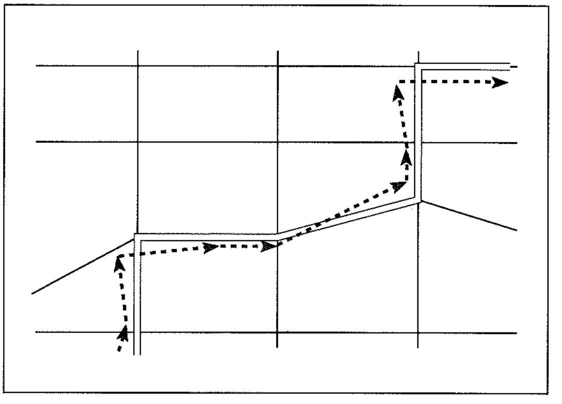

Fig. 43.5 Map matching – identifying a DR path (dashed line) with streets on the map.

By way of an example, one would eventually accumulate significant error using only DR while wandering along city streets. Through comparing the DR path to the map, however, the navigation algorithm can eliminate errors that accumulate from sensor noise. Etak pioneered the map matching approach (see Honey *et al.* 1989) for the Navigator. The Bosch Travelpilot uses the same approach and the Nissan Cedric uses a similar map matching method. Such map matching depends on the driver staying mainly on the roads; it is inappropriate for automatic guidance of a vehicle. In this approach, heading as well as position is determined as an output of map matching and is used for orienting the map displayed to the driver. Experience indicates that the impression given by a map display with a slightly 'wrong' orientation is that the computer is lost or will be soon – somewhat like the impression of a misaligned street name on a printed map. For this reason, map matching methods are used to orient and position the display even for absolute location methods, such as radio location.

Other navigation approaches that have been tried require extensive infrastructure, such as beacons mounted on traffic signal standards. ALI/SCOUT and Autoguide (Catling and Belcher 1989) are examples of such systems. Such approaches can also be coupled with broadcast traffic information. In Japan, the Advanced Mobile Traffic Information and Communication System (AMTICS) project was a test of such a concept (Tsuzawa and Okamoto 1989). The PATHFINDER project in the Los Angeles region is intended to gather information about alternative routes drivers select when provided with traffic congestion information (Wasielewski 1988).

Display and report

All of the commercially available systems display map and vehicle location information graphically on a dash-mounted CRT. Some work has been done to present instructions by voice, but this approach is still in early development stages. Regardless of the method, safety is paramount. Map displays in this context are a dashboard instrument and must provide the needed information at a glance and must not distract the driver. When audio systems become available, they will also be required to facilitate driving, but not distract the driver's attention. As a result, the human interface must conform to dashboard instrumentation design guidelines. For visual displays, this includes letter and symbol sizes in terms of subtended angle for the driver and readability at a glance. In the case of audio output, sounds must be non-distracting and easily understood.

So far as map displays in cars are concerned, heading-up orientation (i.e. displaying the map so that 'up' on the display is 'ahead' on the ground and hence left and right on the display show features that are left and right of the vehicle respectively) makes the display much simpler to understand and read at a glance. In the Etak Navigator and Bosch Travelpilot, the display is heading up with some hysteresis in the heading adjustment to avoid a 'jumpy' display. The Nissan Cedric permits display at only the four cardinal headings and operates in a 'near heading up' mode. In addition, more generalized views provided through smaller scale map presentations are also quite helpful to a driver for choosing routes or just learning context. All commercially available systems provide generalized views. For a map to be readable at a glance, very

Fig. 43.6 Etak map displays at three scales showing few feature labels (courtesy author).

little annotation is possible. All three of the systems mentioned show only four or five feature labels at one time. Figure 43.6 shows three displays from the Travel pilot at various scales, each showing only a few labels. The labels shown were chosen by an algorithm that favours more important streets, the selected destination street and the street on which the car is currently placed.

GUIDANCE TOWARDS A DESTINATION

A primary use of navigation systems is in finding the location of destinations, usually specified by street address but also by street intersection or major landmark, and then finding a way to proceed to the destination.

Destination finding

To find a destination, the map database is searched via specially designed indexes and the destination is shown, for example, on the plot with a flashing star. The driver proceeds towards the star and his or her destination, as it was for the Biblical Star of Bethlehem! In-vehicle destination finding is interactive, may lack a keyboard and – because it is interactive – can take advantage of the user's ingenuity. In the Bosch Travelpilot and the Etak Navigator, for example, there are 12 buttons for input and the user only needs to enter a few characters before selecting from a list of possible cities or street names which match what has already been entered. Figure 43.7 shows a destination entry in progress. The user's ingenuity is exploited for recognizing spelling variants, in contrast to the common practice in geocoding software to search for sound-alike or otherwise similar words.

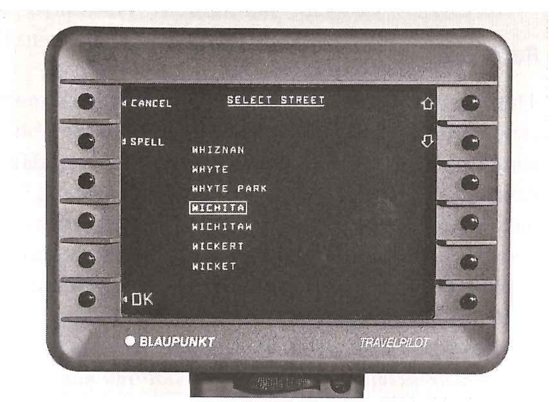

Fig. 43.7 Destination entry to the Etak Navigator.

In the future, business directories ('Yellow Pages') and other lists of destinations will be provided as part of the map. Finding the nearest hardware store or service station is an example of such applications. Detailed business information or advertising could also be provided: for example, restaurant menus may be included. Various experiments are under way to test technical aspects as well as market acceptance of in-vehicle business listings.

Path finding

At the time of writing, only experimental systems such as EVA and CARIN compute recommended paths from the current location to the destination. For pathfinding, the street network topology is required. Furthermore, for the recommended paths to be feasible, the pathfinding algorithm must use traffic flow and turn restriction information; this places a significantly larger burden on the map database. People often expect the guidance system to declare the best route and, ultimately, pathfinding is likely to be a required feature of all navigation systems.

The user interface for the pathfinding function can take many forms. Autoguide, for example, provides only an arrow indicating the action at the next intersection, or a more elaborate graphic for a roundabout. Highlighting the path on a map display is another approach. Two further approaches highlight the path on the map display and offer verbal instructions (Cass 1989).

DIGITAL MAP REQUIREMENTS AND CHARACTERISTICS

A digital map for navigation must meet demanding criteria. It must reside on rugged media, satisfy geometrical requirements imposed by the method of position determination, provide very fast retrieval and use an appropriate coordinate system.

Storage media

The storage medium for all available systems except the Etak Navigator is Compact Disk (CD) (Honey and White 1986). The Navigator uses compact cassette tape. The media and reading device must be sufficiently rugged for vehicle environments and these suffer wide temperature fluctuations and severe vibration. CD players meeting in-vehicle environmental specifications only became available in 1989 and, being designed some years earlier, the Etak cassette player was made specifically to meet in-vehicle requirements for the application. All such devices are relatively slow for random retrieval; typical average seek time for a CD is 1 second – over 30 times that of a typical hard disk. The Etak cassette tape, which operates at 80 inches per second, has typical seek times of 10 seconds. These relatively slow speeds impose noteworthy challenges and severe constraints for the retrieval software, which are discussed below.

Digital maps also consume considerable space. Each CD holds approximately 600 Mb. This is sufficient in EtakMap format to contain all of the streets, with their names and address ranges, in the United States. Etak's cassette tape holds 3.5 Mb, which is sufficient for approximately the same information as shown in two typical folded paper street maps. Inevitably, the current trend is towards Compact Disk because the speed is workable and the storage available is capacious.

Images, vectors, topology and geometry

The simplest digital map representation to acquire and display is the bit-mapped image. It is also the least informative to the navigation software and most voracious in memory requirements. Map matching systems cannot use such images nor are images useful for destination finding. They only support display and, in any event, only at one scale and in one or a very few orientations: thus an upside-down image would not be readable. This is a severe limitation since most systems display the map with the heading of the vehicle being towards the top of the display, the so-called 'heading-up' orientation described above.

A more useful form of map encoding for navigation software is the vector encoding, in which linear features are encoded as directed line segments (vectors) or sequences of segments (see Egenhofer and Herring 1991 in this volume). This encoding is far more compact but is much more costly to acquire. It can support rudimentary map matching and display as well as variations in scale and orientation. Simply coding vectors (i.e. storing the equivalent of plotter commands) is not, however, sufficient for pathfinding nor is it adequate for sophisticated map matching that uses the network topology in its calculations. On the other hand, a geometrical encoding which includes topology fully supports map matching and display. Map matching requires the geometry of the road network for comparing and matching the dead reckoned path with streets; it also requires the geometry for evaluating possible matches against paths permitted in the road network topology. For example, a road connected to the previously 'occupied' road is more likely to be the one currently occupied by the vehicle than one that is not connected but which is near by.

In addition to applications that directly use topological information from the map, the well-known advantages of topological encoding for error detection and control, consistency of feature attribute assignment and control of digital map maintenance all favour such a method of encoding. Furthermore, topological data can be used to improve retrieval speed, which is quite important and is discussed below. Etak uses a topological encoding that also includes generalized views; these are themselves topological encodings of generalized maps computed from the detailed digital map. These views are used for small scale displays and will be used in the future for pathfinding over large distances. In this case, topology in both the fully detailed map and the generalized maps is required for pathfinding.

Retrieval

There are three different types of map retrieval criteria used in vehicle navigation. The first is window retrieval, which is used to retrieve map data surrounding the vehicle or the destination; these data are used both for map matching and display. Second is retrieval by attributes, such as address or street intersection, for destination finding. The third criterion is topological, which is used in pathfinding.

Map retrieval while driving must keep pace with the vehicle. That is, regardless of the vehicle's speed, map data for all the streets surrounding the vehicle must be in RAM for use by the map matching algorithm. Depending on the scale of the display, all or a selection of streets and other features must be in RAM for display. This is a very difficult requirement to meet given the constraints of in-vehicle systems, particularly the slow speed of mass storage and limits on amount of RAM available. For the Etak Navigator, the mass storage is cassette tape and the CPU is an Intel 8088 with 256 Kb RAM. To make retrieval sufficiently fast, Etak organized data so that geographically neighbouring features were usually near by on tape. This reduced the number of searches and the seek time quite dramatically over many GIS implementations.

The constraints for attribute-based retrieval are determined by human factors considerations. The system must find a destination before the user tires of waiting. Typically this constrains the retrieval to 10 seconds or so. Similarly, pathfinding must be fast but probably need not be as fast as destination finding.

Seamless map and coordinate systems

Various coordinate systems have been proposed for use in navigation. Plane projected systems simplify distance and heading computations for dead reckoning and map matching, at least within single map sheets. Complications arise at the seams where projection parameters change. Geodetic coordinates involve more complicated calculations but have the advantage of being seamless, at least over the region that the same approximating ellipsoid is used. The WGS84 ellipsoid is the global reference for GPS (Global Positioning System) and appears likely to be adopted even for systems not using GPS.

For pathfinding, it is necessary to have a connected graph covering the origin, destination and environs. Having unrelated databases for adjacent countries prevents pathfinding from an origin in one country to a destination in another. This means that the map must be topologically seamless, at least at the application software level. Pathfinding software must be able to 'crawl' along the digital street network in a sequence of high level retrieval calls. Seamless topology also simplifies the task of map matching and display algorithms, but these are not quite so dependent on seamlessness.

Digital map production

Providing digital maps meeting the requirements set out above is a huge job and is out of the line of business of automotive electronics suppliers. This fact has impeded development and marketing of navigation systems. Providing electronics alone is not nearly sufficient and mounting a digital mapping effort is expensive and fraught with risk, particularly for companies unfamiliar with the business and technology. Even for companies with considerable experience in digital mapping, the coverage and other requirements for general navigation are daunting. On the other hand, the future navigation market could be huge and the navigation maps are valuable in a multitude of other applications – especially in those countries (like the United States) where provision of large scale and up-to-date mapping has hitherto been sparse.

In the private sector, Etak has produced digital maps for navigation for all major cities in the United States, all of The Netherlands, all of West Germany and various other cities in several countries, including Japan, Argentina, Saudi Arabia, France, England and Hong Kong. Etak sees its business as electronic publishing of digital maps and is building a commercial business accordingly. For source material, Etak uses topographic maps (usually at 1 : 25 000 scale or larger), digital map files, such as TIGER (see Rhind 1991 in this volume), aerial photography, plus various lists of addresses, street names and geographical names and codes. Etak has done some very limited data capture in the field. Navigation Technologies of Santa Clara, California has also produced digital maps for navigation, particularly to support pathfinding for a few metropolitan areas (notably San Francisco Bay and Los Angeles) but has relied much more than Etak on field data capture. TeleAtlas in The Netherlands has produced maps for The Netherlands and has done extensive data capture in the field with specially equipped vehicles. Also, Geographic Data Technologies of Lyme, New Hampshire has provided map data to navigation system developers for US cities. In Japan, Zenrin is providing digital maps containing only major roads to Mazda for its navigation system. Mazda then uses its own manuscripts as the basis for building digital maps.

In the public sector, the Japan Digital Road Map Association (JDRMA) has digitized all of Japan using topographic maps supplied by the government at 1 : 50 000 scale. The Ordnance Survey in Britain has produced the OSCAR data (see Sowton 1991 in this volume) and has provided data for Autoguide covering a corridor between London and Heathrow airport. Several consortia have been formed with the intent of fostering digital map development in a manner which facilitates widespread use of the products. They are discussed in the following section.

STANDARDS

The blossoming of navigation research has given rise to several standards committees and prototyping projects, including the Society of Automotive Engineers (SAE) Committee on Vehicle Navigation, the JDRMA, DRIVE (Dedicated Road Infrastructure for Vehicle Safety), PANDORA (Prototyping a Navigation Database of Road Network Attributes) and GDF (Geographic Data File). Many of these groups have proposed database content and format standards. None of these standards however has enjoyed market acceptance or even market evaluation, since they are not related to commercially available systems. The interested reader should consult the most recent conference proceedings describing these efforts. At the time of writing, the *Vehicle Navigation & Information Systems Conference (VNIS)*, Toronto, 1989, Conference Record offers over 100 papers describing current projects and consortia and much additional material can be found in RIN (1990).

JDRMA has embarked on a ten-year programme of data collection and dissemination and has completed the first phase, digitizing Japanese major roads for urban areas of 200 000 population or greater at 1 : 25 000 scale and rural areas at 1 : 50 000 scale (Kamijo, Okumura and Kitamura 1989). GDF has defined a three-tiered standard for navigation-related map data, including a data exchange standard (Claussen *et al.* 1989). PANDORA is building a prototype database for a corridor between London and Birmingham (Smith 1989).

A different approach to standards is to agree on a software interface. This is analogous to agreeing to a Basic Input Output System (BIOS) interface for personal computers. Etak has adopted this approach in providing its maps and software for use by vendors of other navigation technology (Alegiani, Buxton and Honey 1989). A software interface standard permits flexibility and innovation in storage and retrieval of data just as BIOS permits flexibility and innovation in hardware design and improvement.

CONCLUSIONS

Vehicle navigation is in its infancy but promises to be a voracious consumer of digital maps and GIS technology. Already there are commercial systems available in the United States, Germany and Japan offering street network topology, destination finding by address, intersection and landmark, head up displays and moving map displays. Navigation by dead reckoning and map matching requires maps with a positional accuracy of a car length and street network topology. Radio location, such as LORAN-C and GPS, are alternatives that have not yet emerged as strong contenders for the consumer market and require maps with coordinate information related to the LORAN or GPS transmitters. In the future, it seems certain that the vehicle will contain facilities for providing a variety of information related to vehicle position, location of facilities and traffic. Digital maps and GIS will necessarily play an important role in bringing about that situation.

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EPILOGUE

D W RHIND, M F GOODCHILD AND D J MAGUIRE

The enormous growth in GIS over the past decade or so has left the industry in a buoyant state. To date GIS have been driven largely by technical considerations, although recently the importance of applying the technology has been widely demonstrated. As a consequence, the significance of geographical information science rather than geographical information systems has emerged. It is clear that in the early 1990s GIS have reached a level of maturity such that the 'GIS society' can properly be called a discipline in its own right. The basic principles on which GIS are predicated can be listed, at least in outline terms, and disciplinary trappings such as conferences, journals, textbooks and degree courses exist in abundance.

Future projections, based on current trends, suggest that the number of GIS systems installed will pass the 0.5 million mark before the end of this millennium. Substantial technical developments can also be anticipated, along with a diversification of applications and much-needed advances in understanding the introduction of GIS into organizations. Together, these should assist us in our corporate goal of describing, explaining and predicting Earth patterns and processes with a view to managing the environment, improving human welfare and sustaining our existence in general.

INTRODUCTION

The GIS boom that began in the early 1980s is still accelerating. New vendors are entering the market with new and exciting products, education and training programmes are proliferating, the GIS software industry is reporting rapid growth rates, new textbooks and magazines are appearing, and GIS technology continues to find new applications and new acceptance.

The 1980s were years of unprecedented economic growth, both in Western economies generally and in GIS, and it is clear that the resources that were available to fund this growth in the 1980s will be much harder to find in the future. The 1980s also saw unprecedented changes in computing hardware with the development of personal computing and the workstation. What have we learnt so far – and particularly from the intensive activity in GIS that characterized the 1980s? Where do we stand in GIS research, and what are the important items in the research agenda that remain to be investigated before GIS can really fulfil their promise? What are the prognoses for the future – where will GIS stand in the year 2000?

As we stated at the outset, our objective in this book has been to present a picture of the state of GIS thinking, and the condition of the GIS body politic. This epilogue reflects on that condition in four ways. The first section looks at GIS to date, and reflects on the short history of the field. The second looks at outstanding issues and the research agenda. The third looks into the crystal ball and presents a view of the condition of the field in the year 2000, based on current trends in the GIS market, and predictions about hardware and software. The final section considers the bigger picture, and looks at the social, economic, business and political context for GIS.

LOOKING BACK: THE STORY SO FAR

The technological drive

The roots of GIS go back well into the 1960s (Coppock and Rhind 1991 in this volume) and the field owes a great amount to early efforts at that time by the Canadian federal government, IBM Canada and individuals such as Roger Tomlinson who developed the Canada Geographic Information System (Tomlinson 1989; Tomlinson, Calkins and Marble 1976). In fact the system made a remarkable number of technical breakthroughs, including the use of a scanner and raster/vector conversion; the separation of attributes and spatial data; representation of polygons by arcs; use of chain codes; and the use of Morton order for indexing. It was not, however, until the late 1970s that GIS really began the period of rapid growth that continues today. Several technological developments allowed this to happen (Goodchild 1991 in this volume). On the hardware side, 1980 saw the introduction of the super-mini, a multi-user system with virtual memory management for around $200,000 and a useful platform for a stand-alone, turn-key GIS. On the software side, 1980 saw development of the first GIS to take advantage of a relational DBMS, providing enormous flexibility in the handling of relationships between spatial entities. Finally, 1980 saw the beginnings of the trend towards personal computing and the mass popularization of word processing and desktop publishing.

Today GIS incorporate a remarkably diverse set of interests. GIS applications range from resource management (Robinette 1991 in this volume), through urban infrastructure (Parrott and Stutz 1991 in this volume) to route finding (White 1991 in this volume), from political districting to forestry. GIS run on platforms from the PC to the large mainframe, including an enormous range of software architectures, from the simple, self-contained raster systems such as GRASS and IDRISI to the large database managers such as IBM's GFIS. Some vendors focus on a single platform, while others (notably ESRI) offer a single product over the full range of platforms and operating systems from DOS to VM/CMS. The GIS community includes an extraordinary range of disciplines, from archaeology and landscape ecology through forestry to civil engineering and computer science. Not surprisingly, there is as much variety in the definitions of the field (Maguire 1991 in this volume). GIS are variously described as spatial decision support systems; systems for input, storage, analysis and output of geographical data; or geographically referenced information systems (to cite only three of the competing definitions).

Looking at the development of the field and its current condition raises curiosity about the glue that holds it all together. One major part of that glue is clearly the technology itself, and another is the widespread fascination with processing geographical data. Maps and graphics are interesting in their own right and a computer system that analyses and displays them is doubly interesting. There has been a steady and accelerating improvement over the past three decades in the cost and availability of graphical computing (see below), and this has had an undeniable impact on the growth of GIS. Peter Taylor, in an editorial in *Political Geography Quarterly*, characterized GIS as 'geography's own little bit of the "high-tech" revolution' (Taylor 1990: 212).

It would be grossly unfair to characterize GIS as a technology in search of applications, as this would largely ignore its enormous value to a wide range of its current users. While there may still be some doubt about the exact cost/benefit ratio, the old joke about dividing by zero is clearly inappropriate today in applications ranging from facilities management to forestry, at local and global scales. All the same, reference has been made at several points in this volume (e.g. Aangeenbrug 1991 in this volume; Openshaw 1991 in this volume) to a widely held sense that GIS have not yet found their full potential as tools for exploring and analysing the world, and for supporting human decisions. Instead, GIS seem too often limited to mapping, information management and simple inventory.

The importance of science

The current range of GIS software and hardware products incorporates an impressive range of technological breakthroughs. Concepts such as the TIN (Weibel and Heller 1991 in this volume) and quadtree (Egenhofer and Herring 1991 in this volume) are the direct result of GIS research, and are only two among the many innovative ideas to have emerged over the past three decades. Any technologically-based field must be constantly supplied with new ideas if it is to thrive and needs to be supported by an active research and development community.

However, there is a strong feeling at the present time in the GIS community that the most important issues confronting the field are not necessarily technological. The GIS community seems to be converging not around a single, uniform software product (a standard GIS) or a single application, or around the technology itself, but around a set of generic issues that emerge from using the technology. Whatever the application or data processing solution, every user of GIS faces the same set of problems in dealing effectively with digital geographical data; these problems in turn form the agenda for discussion at GIS meetings – the true glue of the GIS community. Some of the more prominent are:

- *Data capture*: how to convert data from raw to digital form in an efficient, cost-effective manner.
- *Data modelling*: how to represent the infinite complexity of the real world in a discrete, digital machine (e.g. whether to use raster or vector, layers or objects and how to model complex objects).
- *Accuracy*: how to cope with the uncertainty present to varying degrees in all geographical data.
- *Volume*: how to deal with the fact that demands for geographical data will often exceed the space available for storage or the access time which is acceptable (e.g. designing data structures, indexes and algorithms to provide rapid access to large volumes of geographical data).
- *Analysis*: how to link GIS databases with advanced modelling capabilities.
- *User interfaces*: how to present the GIS database to the user in a friendly, comprehensible, readily used fashion.
- *Costs and benefits*: how to measure the benefits of GIS information and compare them to the costs.
- *Impact on organizations*: how to introduce GIS successfully into a complex organization.

All of these issues transcend the technology itself and all of them in one way or another affect the technology's usefulness, whatever the application and whatever the platform. In recent years they have emerged in various guises as the basis of the research agenda of the National Center for Geographic Information and Analysis (NCGIA 1989), the Urban and Regional Information Systems Association (URISA: Craig 1989) and the UK Regional Research Laboratories (Masser 1990; Maguire 1990), as well as in independent assessments (Rhind 1988). Goodchild (1990) has argued that together they constitute a science of geographical information and that the future of the GIS community lies in recognizing a common interest in geographical information science rather than the technology of geographical information systems.

Once the generic issues that underlie GIS are highlighted, and it can be seen that GIS transcend the particulars of the technology and its applications, it is possible to begin to understand how GIS can affect people's view of the world. Traditionally, information about places on the Earth's surface has been stored and transmitted in the form of maps, images, text and to some degree sound. The focus of early GIS was on the digital database as a store of maps which were the input, output and metaphor of GIS applications. Increasingly, GIS are now seen as a means of access not to maps, but to the real world that those maps represent. The purpose of the database must be to inform the user accurately about the contents of the real world, not about the contents of a source document. A DEM, for example, should be assessed on its ability to return the elevation of any point on the Earth's surface, not the position of an abstract contour line.

GIS have also affected the role of geographical information within organizations. They encourage the notion that geographical information is a commodity that flows through the organization, and that has a value determined by its accuracy, currency, accessibility, etc. In fact it may be the central commodity in some organizations such as forest resource management agencies. Collecting and updating geographical data need careful planning and budgeting if they are to be undertaken on a regular basis and are to be accessible to an organization's analysts and decision makers. Finally, if information *is* important, then it is rational to use different types of information as the basis for the organization of departments and systems.

In summary, GIS are a diverse collection of interests, software and hardware solutions, and applications. Two software products applied to the same problem (e.g. ESRI's ARC/INFO and IBM's GFIS applied to management of a utility company's facilities) would produce entirely different solutions. Similarly, the needs of forest resource management and school bus routing appear to have very little in common. There is a growing sense, however, that the issues that hold the GIS community together and produce convergence rather than divergence, are the generic issues of dealing with geographical information, representing it in a digital computer and working effectively with it to produce answers to problems.

The case for GIS as the science of geographical information will probably be debated for many years to come. The complementary argument that GIS are a technological tool for the support of science is presently more widely accepted and is reflected in applications from archaeology to epidemiology. Geography provides a very powerful way of organizing and exploring data, but the map has lagged far behind the statistical table and graph because early generations of scientific computing tools made it so difficult to handle. GIS technology has finally provided the breakthrough, although it remains far from perfect. If we were to draw an analogy between GIS and the statistical software which began to emerge in the 1960s, then the current state of GIS development is probably equivalent to the state of the statistical packages around 1970. But GIS and statistics are ultimately very complementary sets of tools, both capable of supporting an enormous range of scientific enquiry.

To date, the major success of GIS has been in the capture and inventory of features of the Earth's surface, particularly as represented on maps, and in supporting simple queries. There has been much less success in making effective use of GIS capabilities for more sophisticated analysis and modelling (Maguire 1991 in this volume). It is hard to find examples of insights gained through the use of GIS, or discoveries made about the real world. GIS have not yet found widespread application in the solution of major social problems – disaster management, environmental quality, global issues or health. In part this comment is unfair, because such insights would be almost impossible to document. In part the reason is commercial – the market for GIS as information management tools is currently far larger than that for spatial analysis so vendors have invested relatively little in developing and promoting analytical and modelling capabilities. Although current GIS technology is a major improvement on that of a decade ago, it is still difficult to collect, display and analyse data in geographical perspective. Finally, Couclelis (1989) has made the point that the current generation of GIS concentrate on a static view of space occupied by passive objects, offering little in support of a more humanistic view of dynamic interactions.

GIS as a discipline

The current growth of GIS shows no signs of abating and will likely continue for some time into the 1990s. New magazines are appearing, and existing ones, such as *GISWorld and Mapping Awareness*, are growing and increasing their circulation. Conferences are numerous and successful, offering workshops on increasingly specialized topics and access to the latest vendor products. New software vendors are entering the market with exciting and innovative products. GIS are finding new applications and strengthening their penetration into existing markets. GIS courses are proliferating at universities and colleges, and are finding increasing interest from students anxious to acquire useful skills.

On the other hand, there are increasing signs of diversification and this trend is likely to continue to strengthen in the next few years. GIS applications such as facilities management fall under the spatial information paradigm, whereas scientific and resource analysis applications fall under the spatial analysis paradigm. The former emphasizes the database and query aspects of GIS, whereas the latter tends to focus on modelling. The split is illustrated by the case of two Canadian companies – TYDAC and GeoVision – the former marketing 'spatial analysis systems' with the very successful SPANS product, the latter marketing 'geographical information systems'. Within the PC marketplace, there is increasing divergence between products aimed at GIS applications such as resource management, facilities management and market research (compare, e.g. PAMAP, TYDAC's

SPANS, Facility Mapping Systems' FMS/AC and Strategic Mapping's ATLAS*GIS).

This trend to diversification is appropriate and rational, as it matches software and platforms with different functions and applications. The complex modelling and analysis of resource management requires a very different solution from intensive digitizing or the management of large facility inventories. In time, we can expect this trend to lead to more and more specialization within the GIS industry, as it becomes less and less possible to offer a single software solution for all platforms and all applications. One vendor may specialize in digitizing stations using PCs, another in database maintenance using large mainframes and terminals, another in spatial analysis using advanced personal workstations, and another in 3-D applications.

There is an interesting analogy between the development of GIS and the history of communication. The written letter, an analogue format, was first replaced by the digital telegraph, then by the analogue telephone. Electronic mail, a digital format for transmitting text as a string of characters, is now in competition with FAX which transmits an uninterpreted image of text. Having spent the past three decades working to replace the analogue map with the digital GIS database, we are only now beginning to realize that there can be great value in combining other types of information, particularly images, text and even sound, with GIS. The multimedia GIS is already functioning in many highway maintenance organizations, where digital or video-format images are linked with GPS-determined locations in a digital database, and multimedia GIS are also finding applications in resource management and marketing. In part this is a technical problem, as the software and hardware tools to manage multiple media have only recently become available, most prevalantly in the Macintosh world. But it is also a conceptual problem, having to do with the role of the symbolic map in GIS thinking. If GIS are a window on the world, then it makes sense to combine the view provided by the highly structured and interpreted database with other media, whether digital or analogue. We tend to see the structured GIS database as exclusive, and to know little about the relative value of other media.

Despite this sense of growing diversity in the GIS community, there is evidence of convergence. The past few years have seen the emergence of several series of conferences aimed at the full GIS community. In the United States, the annual GIS/LIS series sponsored by a consortium of five societies (AAG, ASPRS, ACSM, AM/FM and URISA) has grown quickly to over 3000 attendees (Morrison 1991 in this volume). In Canada, the Ottawa meetings in early March have been similarly successful. The lone textbook of 1986 by Burrough (*Principles of Geographical Information Systems for Land Resources Assessment*) has now been joined by several others (e.g. Aronoff (1989) *Geographic Information Systems: a management perspective*; Star and Estes (1990) *Geographic Information Systems: an introduction*) and many more are on the way. (See Maguire 1991 in this volume for a list of GIS textbooks.) New organizations have appeared and the Association for Geographic Information (AGI) in the United Kingdom seems to be a particularly successful example; and GIS technology now has its own journals. A large number of higher education institutions now offer Masters' courses and several even have undergraduate courses in GIS (e.g. Kingston and North East London Polytechnics in the United Kingdom).

All of these would be recognized in the sociology of science as symbols of an emerging scientific community – in short, a discipline. But unlike physics or biology, GIS have no fundamental problems to solve of the magnitude of the origins of the universe or the basis of life. One view holds that GIS are merely a tool, and that the GIS research community must wither away as the tool reaches perfection. Another, presented at some length above and amply illustrated in the chapters of this book, holds that there are fundamental issues in GIS – not so much in the tools any more as in the use of the tools. Alternatively, perhaps GIS are like statistics – a tool to most scientists, but a set of fundamental research problems to the parent discipline.

If GIS technology is a discipline, then it is clearly not 'owned' by any traditional one. Geography, cartography, surveying, photogrammetry and engineering have all been accused from time to time of trying to dominate GIS – but with little success as GIS are fundamentally an interdisciplinary field. Whether GIS develop the institutional structures of a discipline in its own right, like statistics, or remain an interdisciplinary consortium of interests like remote sensing remains to be seen.

LOOKING AROUND: WHAT REMAINS TO BE DONE

It is becoming increasingly impossible for any one vendor to be all things to all GIS users – to offer one product on all platforms, under all operating systems, as a solution to all applications. One way to view specialization in the GIS industry is in terms of three measures: functionality, capacity, and accessibility. Ideally, a GIS should offer a wide range of forms of spatial analysis and manipulation on a large and accurate database, and provide responses immediately. In practice, these objectives conflict. Fast access to large databases is feasible only if the number of possible operations is severely limited and systems that offer complex modelling and analysis often restrict capacity. In GIS there can be no limit either to functionality or to capacity, since users will always find reasons for more.

If the future of GIS lies in specialization, then the key to success will be standards. Encouraging progress is being made in data exchange formats (e.g. USGS's SDTS, DMA's DIGEST and the UK NTF) and in standardizing terminology (DCDSTF 1988; Guptill 1991 in this volume). But terminology is notoriously difficult to standardize. For example, there is little indication to date that the proposed term for the common boundary between two polygons ('chain') will replace those in current usage ('arc', 'segment', 'edge', '1 cell', etc.). It is also difficult to standardize when the central concepts of GIS are so poorly articulated. Key terms such as 'raster' and 'vector', 'object' and 'layer' need to be standardized if we are to develop a well-defined set of data models. Standards are needed for data sources, particularly in describing quality, and for user interfaces. However, the diversity of the GIS community makes the development of standards difficult. For example, the needs of the US Bureau of the Census in a street network database are very different from those of the vehicle navigation industry, or the emergency response community, or the highway maintenance authorities.

Despite their importance, standards will do little to solve many of the more pressing problems of GIS. The field is only now beginning to come to grips with the issues of uncertainty and accuracy (Fisher 1991 in this volume; Chrisman 1991 in this volume) and, while recent research has led to significant advances in understanding how uncertainty propagates through a GIS (Goodchild and Gopal 1989), it will be a long time before the accuracy requirements of GIS have significant impact on the process of geographical data collection and compilation. New and exciting concepts in data modelling, such as object orientation, are only now beginning to influence the field and much remains to be done in exploiting the ideas emerging from current research on user interfaces (Frank and Mark 1991 in this volume). If GIS research of the 1960s and 1970s was primarily directed at solving the technical problems of geographical data handling, allowing a significant industry to emerge in the 1980s, then the 1990s will be the decade in which the cycle reverses itself – when new concepts emerge from the application of the technology to affect conventional ways of thinking about geography. GIS are only now beginning to impact on the organizational structures of public agencies, the traditional providers of geographical data, conventions of map making, or the urban planning process.

Among the larger research issues still to be resolved are the following:

- How does GIS complement other technologies for handling geographical data, such as maps, atlases, text descriptions, or images? Should all of these be implemented in a digital environment, or can digital and analogue technologies complement each other?
- How will GIS, GPS and other novel technologies affect traditional methods of geographical data collection and compilation? Will the role of mapping agencies increase or diminish in the coming decades?
- How will the flexibility of digital geographical databases affect the role of geographical data in everyday life, which is now so closely geared to the paper map?
- How will the rigorous, objective perspective of GIS be adapted to the imprecise, subjective world of human reasoning and decision making? Will it be through the development of spatial decision support systems, knowledge-based or expert systems, or will the two paradigms find themselves incompatible?

Much also remains to be done in education and training. Vendors and institutions have already responded to the critical shortage of staff by adding courses and programmes and the US NCGIA has developed and published a one-year course sequence (Goodchild and Kemp 1990). But GIS is still a novel field, and courses are often treated as add-ons to existing programmes, and rarely integrated into full curricula. There has been some discussion of integrated curriculum requirements in the literature (Nyerges and Chrisman 1989; Unwin and Dale 1990) and vendors are increasingly willing to offer more than simple training programmes. But GIS education remains an issue, intimately linked with the previous discussion of the nature of GIS as a discipline.

Much also remains to be done at the organizational and institutional level. The potential for sharing data between agencies remains unrealized in most countries because of traditional interdepartmental barriers. The development of standards is similarly impeded by a lack of coordination and leadership. The organizational structure of many public agencies continues to be dominated by the needs of traditional methods of map making and geographical data handling. In the new digital environment it is vital that the public agencies adopt a lead role in coordinating research and education programmes, in ensuring the health and vitality of the GIS industry, and in defining standards of data quality, data formats, etc. This is particularly important at a time when public sector funds for traditional map making are steadily diminishing.

In many areas the future of GIS will continue to be determined by developments in hardware – technological innovation will continue to influence GIS as long as new ideas continue to drive the computer industry. The cost per cycle will continue to drop in the next few years, as will the cost per megabyte of RAM. The 1990s will see the proliferation of 3-D technology, as high performance graphics adaptors become available for mass-produced workstations from vendors such as Silicon Graphics. The recent generation of workstations, typified by the IBM RS/6000, include 3-D adaptor options with display rates as high as one million 3-D vectors per second, with polyhedral rendering capabilities, in a platform running at 25–45 MIPS (Million Instructions Per Second). GIS will no longer be confined to the plane, and the DEM display capabilities of today will seem very primitive in a few years. It will become possible to model and visualize subsurface conditions, and to analyse distributions over the surface of the earth without the distortions and interruptions produced by conventional map projections. In 3-D, the map metaphor is completely inadequate and the user interfaces for these systems will have to explore entirely new territory. How, for example, should a system allow the user to build knowledge of subsurface conditions from a variety of different types of evidence? In 2-D, this task of map compilation takes place on paper but in 3-D it can only take place in the abstract domain of the digital database. What tools does a user need to explore a model of the subsurface once it has been built? What icons should be provided in an appropriate user interface?

If GIS have been dominated thus far by the map, then fundamental changes now occurring in mapping will have significant effects in the coming decade. Low-cost GPS receivers are already available with higher accuracy than the base mapping available over most of North America (1 : 100 000, 1 : 24 000 in continental United States) and many areas of the rest of the world. GPS also provide a significantly cheaper method of primary data collection for many mapping activities. This system is already being used to map road and rail networks, and to track vehicle movements. At the same time the funds available to support large, public-sector mapping programmes are diminishing.

Current prospects for the future

There seem to be two contrasting views of the prospects for GIS in the coming decade. The first is negative and the second positive, and it seems more likely that the second will prevail. However, there are actions that can be taken to strengthen the odds.

In the negative view, GIS will fragment and disappear, and by the end of the decade will be nothing but a memory. Geographers often draw a parallel between GIS and the introduction of quantitative methods to geography in the late 1960s (Taylor 1990), and comment on the lack of interest in quantification, at least in human geography, in the 1980s. On this view GIS will fragment because the system is too loose to hold together and because the glue is too weak and abstract. Users of IBM's GFIS, ESRI's ARC/INFO and Map/Info will cease to see any reason to attend the same conferences. The consortium of five organizations responsible for the North American GIS/LIS conference series will break up and each will concentrate on its own agenda. GIS will be seen as the Edsel of EDP, too awkward, complex and expensive except in some specialized applications.

In the positive view, the GIS consortium will continue to converge. A constant supply of better tools seems assured, particularly in computing speed, software integration, network communication, graphics and storage capacity. The infrastructure of the GIS community will continue to improve, with better magazines, organizations, textbooks, meetings, and all of the symbols of an emerging speciality. Less assured but essential is a constant supply of new players in the industry, since the pattern has been that new players are the source of a disproportionate share of technological innovation. New players such as Prime/Wild with System/9, SmallWorld, or Strategic Mapping with ATLAS*GIS bring new ideas to the industry.

In the positive view, the public agencies will promote and develop standards for data exchange formats, structures, models and data quality. Training and education programmes will develop through cooperation between vendors and institutions, and lead to the emergence of a strong set of core concepts. Funds will be available through cooperative agreements to support the development of teaching facilities, and to ensure that these keep pace with developments in the technology.

The results of research currently under way will emerge in improved products. Of particular significance will be:

- data models to handle 3-D and time dependence, and complex interactions between objects;
- support for complex analytical applications, including tracking of data lineage, tools for visual interaction with the stages in the analysis process, propagation of uncertainty;
- support for quality assurance and quality control (QA/QC) especially in GIS applications where litigation is a constant problem;
- support for multiple media – unstructured images, both digital and NTSC, text and sound;
- integration of GIS with the capabilities of GPS for data collection and compilation;
- tools for visualizing 3-D and time-dependent data;
- tools for data compilation, particularly in 3-D;
- improved techniques for conducting functional requirements studies, evaluating costs and benefits, benchmarking and other aspects of the GIS acquisition and project management process.

Finally, the GIS community will converge around a common concern not only for the technology of GIS, but more importantly for the common issues that transcend the technology and pervade all applications. GIS can survive by constantly developing new and exciting capabilities, or by constantly finding new applications. The really fundamental issues in GIS, however, are those that are common to all users of geographical information – how to capture a complex and dynamic world in a digital database and provide access to it in a useful, accurate and cost-effective manner.

LOOKING FORWARD: GIS 2000

All of the above is based upon our (considerable) collective experience in GIS and discussion with many colleagues. But it is also sensible to attempt to quantify some of our predictions: such forecasting is, for instance, central to all business planning and resource allocation. Inevitably, though, all such forecasts become less precise as the time period becomes more extended, but two basic techniques exist for predicting the future. The first is to project existing trends within the subject area and this is normally a sensible strategy in the short term, say for two years. The second is to analyse and understand what underlying changes are taking place in society or the environment as a whole, then to assess how long the effects of these will take to work through to individual sectors such as GIS. In this section, we attempt – briefly because of the paucity of the evidence – to use both methods in order to understand what is likely to happen to the future of GIS. In so doing, we avoid (wherever possible) technical and other details. It is all too easy to write about the subject at the 'nuts and bolts' level of detail; indeed, that is where the great bulk of applications work thus far has been carried out and where most of the technical work seems to be directed. Moreover, dealing with detail is often immensely satisfying: the possibility of error is reduced to minute levels if the topic is reduced to the mechanical and the specific! But we need to deal with broad issues involving many intangibles; inevitably, then, we will get some of them wrong.

Trend projections

The simplest and probably the most reliable trend to project is that of hardware performance. Figure E.1, produced by the British consultants Price Waterhouse, shows the rapid diminution in cost of one measure of computer power – MIPS or million instructions per second. In practice, this is often a most misleading statistic, but its trend parallels that of most other measures of performance. Over the last 30 years, there has been about an order of magnitude decrease in cost of computing power every six years. What cost $1 or £1 to compute with state-of-the-art equipment in 1990 cost about $100 000 or £100 000 to compute when Tobler (1959) wrote his famous seminal paper on automated cartography. More recently, things have been changing even more rapidly. A simple way of describing the current growth in computer power is to consider a Digital Equipment Vax 11/780 of 1984 with 1 MIPS power; the growth in power for the same cost since then can be approximated by the expression:

$$MIPS_{year} = 2^{(year-1984)}$$

Hence, for 1991, MIPS = 128

Moreover, data storage with similar characteristics (such as direct access capabilities) has decreased in cost at similar rates. The bulk of computers has diminished as rapidly as has their reliability increased. The drawing speed and resolution of output displays has changed from the slow, coarse and relatively expensive storage cathode ray tubes of the 1970s to the million colour, 300 000+ vectors per second and modestly priced workstations of today (Goodchild 1991 in this volume). If this trend is spectacular, it shows no signs of conclusion: all the indications are that even 'traditional' computing engines may be made to go substantially faster and will become still cheaper. Moreover, it is evident that parallel processing (see, for instance, Dowers *et al.* 1990) will provide further increases in performance once the myriad of algorithmic and software problems have been resolved (Franklin 1991 in this volume). Finally, perhaps the most important development in hardware other than general-purpose computing engines is the rapid improvement in performance/cost ratio for Global Positioning Systems (or GPS); to be able to establish absolute position in three dimensions anywhere on the Earth's surface with an accuracy of metres, all achieved within a few seconds, is likely to revolutionize surveying practice, generate many more GIS-type applications and improve existing embryonic ones like vehicle navigation (see White 1991 in this volume).

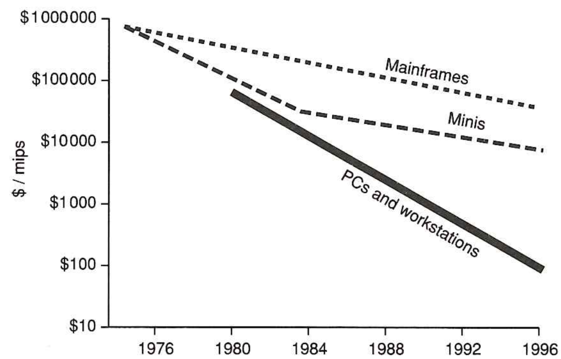

Fig. E.1 Hardware price performance trends. (*Source*: Price Waterhouse (1991).)

Costs of software can only be traced from the early 1980s since only then were the first commercial GIS available (Coppock and Rhind 1991 in this volume). Over that period, we have seen a decline in costs, accelerating as more and more systems arrive on the market. Thus the list price for a minicomputer version of ARC/INFO in 1983 was about $100 000 (or about $200 000 at 1990 prices); in 1990, a first copy for a 386-based computer of like performance (but with much more software functionality) was about $10 000, with heavy discounts for multiple copies. In practice, such list prices are rarely paid; most vendors will discount to many classes of customers and some have given GIS software to organizations purchasing hardware; it is thus difficult to quantify the trend precisely but dramatic price reductions and increase in quality of the product have occurred simultaneously. The extent to which this can go on is unknown, except in the mass market where GIS are sold for PCs and low cost workstations in a manner analogous to dBASE, Lotus 1-2-3, Excel or even word processing packages like Word and WordPerfect. If this occurs, we should expect to be able to buy fully functional GIS for about $500 in the mid-1990s.

All of the market surveys carried out in Europe and North America at the time of writing this book paint a story of increasing use of GIS and related data sets. Unhappily, little comparable evidence is available for other areas of the world. The surveys show global sales of between $500 million and $4000 million per annum for GIS software, hardware, services and data, the sum varying with information source, with the definition of GIS adopted and with the base year taken (see Maguire 1991 in this volume). All surveys are unanimous that growth in the total expenditure by users is of the order of 20 to 30 per cent per annum. Some individual vendors such as ESRI report growths of income of over 40 per cent per annum. This and the ubiquitous nature of GIS applications has led organizations such as IBM to identify GIS as an area on which to concentrate (see Dangermond 1991 in this volume).

The immensely broad spectrum of what different individuals consider as a GIS complicates establishing a benchmark of the number of systems now in operation. Based, however, on sales of systems of known capabilities, there were not less than about 20 000 installations world-wide in 1990 with at least significant claims to being a GIS. In early to mid-1990, annual sales seemed to be running at about 6000 systems per annum, including PC products. The advent of new low price systems such as Atlas*GIS later in that year made the forecasting of sales very much more difficult. Assuming, however, a 20 per cent per annum growth rate in GIS-related expenditure by users and a 40 per cent growth rate in the number of systems (because of the much faster growth in the number of small-machine than large-machine systems), the figures for sales and system numbers at different dates would be as indicated in Table E.1. It should be stressed that this is nothing more than projection of trends, assumed to be constant in proportional terms (i.e. exponential), from an uncertain base and over a time horizon during which the market will certainly change both qualitatively and quantitatively. None the less, even if these trends only hold up for a short period, the implications are enormous.

Table E.1 GIS trends 1990–2000

Year	1990	1993	1996	2000
Sales ($million)	1000	1750	3000	6200
Number of systems ('000s)	20	55	150	580

It is also entirely possible that these figures may be achieved despite apparent saturation in certain markets and in particular areas. Thus, for instance, we might expect the market for GIS in utility organizations within developed countries to be saturated by the late 1990s but for growth of that market to expand in other currently less developed countries. In addition, all the current indications suggest that growth in use of systems for environmental, health and other purposes will more than compensate for any 'flattening off' in demand for systems within the 'early adopter' sectors. Overall, most GIS applications thus far have been at the inventory or monitoring level – computing taxes, routing vehicles and assessing the extent of change in the natural environment. This is really little more than transaction processing and periodic reporting on the overall level of some activity. Such functions are often critical: the very life of cities may break down if taxes are not collected, if assets are not managed properly and resources allocated effectively. But it is at least arguable that the use of GIS in modelling, in prediction and in supporting high-level decision makers, policy makers and politicians is as important as inventory tasks, if not more important, and that the former will come of age before the end of the millennium.

LOOKING TO THE WIDER SCENE: THE SOCIAL, ECONOMIC, BUSINESS AND POLITICAL CONTEXT TO THE YEAR 2000

Irrespective of the means employed, prediction of the future is highly error-prone, as the substantially unexpected collapse of Communism in the nations of Eastern Europe in 1989 and the Gulf War of 1991 within six months of the Iraq invasion of Kuwait have demonstrated. In particular, trend projections never anticipate the broad patterns of change through history. While acknowledging the dangers involved, it is appropriate in this Epilogue to stand back and to examine the societal context in which GIS operates; from this, and an attempt to predict how this context will change, we can at least surmise how the use and form of GIS will be effected up to the end of the twentieth century.

We take the following societal changes at least to be likely:

- The 'internationalization' of national economies will continue to the extent that the economies of few, if any, countries will be unaffected by the state of global trade.
- There will be increasing levels of activity by multinational corporations and, as a proportion of the global market, a diminishing share will be held by national-only suppliers.
- Increasing levels of competition between states and between individual vendors will be the norm. Yet, despite free-trade agreements, multinational trading blocs such as the European Community will still attempt to foster indigenous developments and products.
- The acceptance and implementation of international standards will lead to increasing convergence of products, at least within individual market sectors.
- The need to maintain economic operations in a highly competitive market may ensure that only major vendors capable of financing new products, packaging and maintaining them and advertising appropriately will survive (except in niche markets). Set against this need for massive resources, of course, is the fact that small firms have thus far always been the source of innovation in the computing industry and that large firms not only become ossified but suffer the burden of having to support earlier systems in an upward-compatible manner. While the 'big and old' versus 'small and new' battle is unlikely always to be resolved one way, big and sclerotic firms will go out of business as well as those small ones unable to fund (by today's standards) very well packaged and reliable products.
- Labour-intensive operations will increasingly be exported to areas of low labour costs.
- The level of global prosperity as a whole will continue to increase, but may continue to decrease in some areas such as Africa (see Taylor 1991 in this volume).
- Societies are going to become increasingly protective over the confidentiality of data relating to individuals.
- Individuals, corporations and governments are increasingly going to take the use of computerized databases for granted and, as a consequence, more are going to be created.
- Information in general (and geographical or spatial information in particular) is going to become more and more of a commodity in most parts of the world and be treated as a valuable resource – with obvious commercial consequences.

The implications for GIS of societal changes

From all of the above, we can conjecture the following:

- We will see a convergence in general-purpose GIS, with most systems running under UNIX, and functionality (though not necessarily the ways of providing it) becoming more and more similar between different products. Interfaces will also come to share more common properties, whether through a standard spatial language (perhaps applied *post hoc*, via a universal dashboard which can be applied to any system – see Raper and Rhind 1990) or simply through use of similar menus, or because of the widespread use of the X-Windows Graphical User Interface (GUI).
- Notwithstanding such convergence, sector-specific products will probably appear. In part this will arise because the concept of an all-embracing GIS may well become impractical and in part because of market differentiation (see below).

- Vendors will attempt to differentiate their products in a number of ways. These will include: the efficiency of coding; the adaptation of their toolboxes to operate as 'self-contained and friendly' systems in important core markets such as the utilities; the production of spin-off products (such as ARCView); the transparent linkage of the GIS code with other functions such as modelling, accounting (e.g. spreadsheet), statistical and presentation graphics packages; the production of better training and documentation than their rivals; the production of 'national-specific' versions (see below); and through support of a variety of 'friendship' schemes such as user clubs.
- The market for GIS will attain the stage already reached by the Information Technology market as a whole so far as the world's biggest players – IBM and DEC – are concerned: the bulk of the market will lie outside the United States.
- Challenges to the US supremacy in software may well come from sources such as Japan and Europe.
- Political factors will ensure that software and system creation will need to be carried out in multiple locations. By analogy with car manufacturing in the 1980s, system creation will need, for instance, to be carried out by US and Japanese firms within Europe if they hope to be treated on equal terms with indigenous producers. Since there is a real possibility that the European Community by the year 2000 may include 20 countries and a population of nearly 500 million relatively affluent consumers (or almost twice that of the United States), this seems a matter of importance for all non-European-based vendors.
- Even ignoring the political case for local system creation, users will increasingly wish to see local customization in global products, such as the use of the local language – with all that implies for user interfaces, for the use of diacritical marks, etc.
- Digitizing, to accepted *de facto* standards, will be done wherever it is cheapest. Thus, manual digitizing contracts may well be carried out in China or elsewhere in South East Asia or in Eastern Europe. Mass digitizing may well die out in North America and Western Europe unless scanning and subsequent feature recognition and vectorization can be made routine and cheaper than the manual, 'off-shore' digitizing.
- In any event, the peak of the mass digitizing will be just past in the United States, and long past in the United Kingdom and several other countries by the year 2000. The topographic base maps and the utilities' networks will by then mostly be digitized (at least on all current projections). Thus the source of material for mass digitizing will increasingly come from areas outside that of the pioneers.
- This decline in mass digitizing will be accompanied by a growth in the routine use of direct position-fixing by use of GPS receivers. This may cause significant problems because the readings obtained may be more accurate than maps to which the data can be compared. Map revision by national mapping agencies will, therefore, be necessary though some of this may be achieved by use of 'rubber sheet' transformations using enough control points.
- GIS technology may well have disappeared as a 'free-standing' activity in many organizations as its functionality becomes encompassed by business-oriented systems, such as those for market analysis, and it becomes part of wider Management Information Systems.
- The data volume problem will have disappeared so far as certain applications are concerned, but will remain acute for others. In dealing with population and other censuses, for instance, storage technology is improving much faster than population growth! Given reasonable data compaction routines, it should be possible to hold about 30 items of information for every person in the United States or in Britain, France, Italy and Germany on a single CD-ROM disk whose current reproduction costs are about $1 if produced in reasonable numbers. Even this storage capacity, however, palls into insignificance when contrasted with the need to hold the volumes of data produced from satellite imagery of the natural environment; global applications in particular seem likely to extend the range of hardware and software for decades to come.

- Much the greatest threat to widespread use of GIS comes from the data supply policies of those governments which require commercial returns to be made to the state for information already collected for the purposes of state administration. The ownership of data seems inevitably destined to become part of the competitive process and, as such, to affect the abilities of those in education in particular to carry out research and teaching relevant to the needs of the outside world except by forging intimate and individual links with data suppliers.

- Given all this and diminishing real costs of computing power, we expect to see a dramatic growth in 'value-added services'. These will include the use of GIS to combine data sets to meet the needs of specific customers, the use of skilled personnel in 'information literate' organizations to provide expert (and legally defensible) interpretations of geographical data sets for customer organizations and the provision of services for 'end-to-end' data compilation, analysis and interpretation when required.

- We suspect that the degree of concern over privacy and confidentiality of data will continue to be much greater for socio-economic data than for that pertaining to the natural environment (though emissions of pollution and like measures are obvious anomalies). In practice, GIS technology will have to grow much improved security facilities, but it also offers one major advantage: by offering the possibility of working at the area aggregate level and still permitting the linkage of different data sets, GIS can carry out analyses without infringing confidentiality restrictions on individual level data. The price to be paid for this is the set of problems which Openshaw (1991 in this volume) and others have described in this volume. Answers to analyses – at least using conventional statistical analysis tools – differ depending on what type and size of areal units are used. Clearly systems must be able to cope with such problems, or at least warn the unsuspecting users of the danger of data-induced artefacts.

- At the end of the day, the success of many applications of GIS will depend for the foreseeable future upon the skills and professionalism of the individuals involved – irrespective of the success of expert systems. Indeed, because of the fuzzy nature of 'rules' currently followed in manually based analyses, the success of artificial intelligence (AI) in GIS may yet turn out to be small. It is essential, therefore, that GIS operators have access to proper training, carried out to certified standards, and to chartered status. In practice, the latter may most easily be achieved by adding GIS to the training of engineers, planners and surveyors, rather than creating a new chartered, professional institute. However it is done, something of this sort is essential if GIS is to become an accepted part of professional judgement and risk taking, and if insurance of new schemes is to be obtainable. Education and training in future, then, will have to concentrate as much upon setting and demonstrating standards as on the curriculum content.

CONCLUSIONS

As we write this book, many already think of GIS as a mature discipline. Yet, as we have shown in the previous pages, there are still major shortcomings when GIS are used for certain purposes. Current research in progress will solve many of these yet, as the demands and range of users grow, presumably other problems will appear. While we expect many fundamental changes to occur in GIS – notably the decline of the 'map processing model' on which much early work and training were based – we are also clear that the best guide to the future is the recent past. We confidently expect, therefore:

- the further expansion of GIS concepts, tools and practice into a steadily widening range of roles;

- major technical developments and reductions in the price of hardware and software;

- the almost ubiquitous use of GIS in local and central government, in much business and in research and education;

- the rise of global applications and the recognition that GIS are crucial components of Management Information Systems.

All of these developments will assist us greatly in achieving our corporate goal of describing, explaining and predicting the Earth's patterns and processes with a view to managing the environment and sustaining our existence.

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