GEOMATICS AND GEOGRAPHIC INFORMATION SCIENCE: TRANS-CENTURY DIRECTIONS AND APPLICATIONS

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1. INTRODUCTION

Recently there has been much discussion of what it means to is "doing GIS" in an academic setting. In a recent article (Wright *et al.*, 1997), Dawn Wright, Jim Proctor, and I explored this question, and identified several possible answers:

- doing GIS means using a combination of software, hardware, data, and communications to solve some spatially-explicit problem;
- doing GIS means developing algorithms, data models, or other elements of geographic information technology;
- doing GIS means working to advance our understanding of the principles, concepts, and theories on which GIS is based.

We concluded in the paper that only in the last sense was someone who claimed to be "doing GIS" also "doing science". Clearly there is much confusion and debate about the significance of GIS, and how it fits into the broader academic and intellectual enterprise.

That paper was aimed at an audience of academic geographers, who worry about the place of GIS within the discipline of geography, and about narrower issues such as the importance of GIS in the undergraduate curriculum, and the demands placed by GIS on the departmental budget. More broadly, I think it is possible to identify four distinct views of GIS:

1. GIS is a mature and distinct application of electronic data processing comparable to word processing, or spreadsheets.
2. GIS is a branch of engineering, concerned largely with the practice of spatially-explicit problem-solving.
3. GIS is an immature technology whose further development requires significant advances in research.
4. GIS is a technology that requires a strong conceptual and theoretical framework that has yet to be developed.

Each of these four views suggests different analogies and metaphors. The analogy in (1) to word processing leaves no room for fundamental significance, firmly relegating GIS to a 'mere tool'. (2) suggests other branches of engineering, and has obvious links to the surveying tradition. (3) and (4), on the other hand, suggest that GIS, or the research and theory behind GIS, are a significant branch of science, analogous to computer science, or information science, or statistics.

Over the past decade there have been several efforts to clarify this diversity of views by introducing terms that are more clearly identified with fundamental issues, and less with technology. *Geomatics* has proven popular in some countries, and among specialists whose GIS roots lie in surveying, photogrammetry, and related disciplines. *Geographic information science* or *GIScience* (Goodchild, 1992) is also popular, particularly in the U.S., and tends to be more strongly associated with roots in cartography, geography, and related disciplines. There is obviously substantial overlap between the two terms, and little to be gained by attempting to distinguish them. My own disciplinary background clearly ties me more strongly to GIScience, and I will use that term throughout the paper.

The next section of the paper discusses major research challenges in GIScience, first using the consensual

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research agenda developed by the U.S. University Consortium for Geographic Information Science, and then focusing on some suggested *grand challenges*. The subsequent section turns to applications, distinguishing between applications of GIS on the one hand, and applications of GIScience on the other. The paper ends with some thoughts on directions for GIScience at the millennium.

2. THE UCGIS RESEARCH AGENDA

One of the most useful views of the research agenda of GIScience emerged from the first Annual Assembly of the U.S. University Consortium for Geographic Information Science, an organization founded in 1995 and including now of some 47 academic institutional members, plus other organizations and laboratories. More details of the consortium and its research agenda are available at its Web site (*www.ucgis.org*), and a summary of the research agenda has appeared as a journal article (UCGIS, 1996). The process for developing the agenda included voting by each of the delegates from the member institutions, as the culmination of a consensus-building exercise, so the agenda clearly reflects the views of the organization as a whole. The next sections discuss each of its ten priorities or challenges in turn.

2.1 Spatial data acquisition and integration

Our ability to solve spatially-explicit problems is limited by the available data, which is in turn a function of our ability to sense geographical phenomena using automated or remote means, or to afford the very high costs associated with collecting data on the ground, by direct human observation. Remote sensing also offers the advantages of global coverage, where permitted by satellite orbits and where this does not conflict with concerns for privacy and national sovereignty. New satellites that are likely to come on stream in the next few years will offer significant improvements in spatial and spectral resolution.

With more and more sources of data, it is becoming increasingly likely that more than one source exists to satisfy a given need. For example, our recent experiments with street centerline databases in the Santa Barbara area (see *www.ncgia.ucsb.edu/vital*) have made use of six different and independent sources, some commercial and some public-sector. The UCGIS research priority in the area of integration reflects the need for basic research into methods for combining data sets, resolving positional and semantic differences between them, and extracting the best information from both. We do not yet have the ability to apply methods to spatial data that are comparable to weighted averaging with simple numerical data.

2.2 Interoperability of geographic information

Just as today there are often many sources of data representing the same phenomena, it is common to encounter differences resulting from the presence in the market of many competing forms of GIS software, with different standards, formats, terminology, and practices. It is difficult for a user trained on ARC/INFO, say, to work with an Intergraph product, because the terms, commands, and 'look and feel' are very different. Similarly it can be very time-consuming to have to transfer data from one system to another, or to integrate data from a variety of different sources.

This problem of lack of interoperability exists because GIS developed in an *ad hoc* fashion, in the absence of any well-accepted set of principles or theories to provide a frame of reference for how to do things. The Open GIS Consortium is busy building interoperable specifications, but is similarly hamstrung by the lack of strong theory. Thus the research community has a very powerful contribution to make, and recent research is finally beginning to move in the right directions (see, for example, Goodchild *et al.*, 1998; Vckovski, 1998).

2.3 Distributed and mobile computing

The technological progress represented by the Internet, the Web, and wireless communication is having massive effects on the nature of computing, and what is possible in the handling of geographic information. It is now possible using the connectivity provided by the Internet to store and process information at locations that are almost completely independent of the location of the user. Instead of obtaining data and mounting it locally in a geographic information *system*, the user can send specifications for a geographic information *service* to a remote server, obviating the need for local storage of data, a local GIS, and even local processing power. Moreover, wireless communications now allow activities in locations far removed from the wired connections of the traditional Internet.

These changes raise profound questions. If computing can occur anywhere, but must nevertheless occur somewhere, what criteria define a rational basis for choosing locations? Is it possible to develop a location theory of computing, analogous to classical location theories of industrial or service location? What new techniques can be devised for searching for data, software, and services on a distributed network? What new activities are enabled by the ability to operate GIS in the field?

2.4 Future of the spatial information infrastructure

In the U.S., the term *National Spatial Data Infrastructure* has come to serve as an umbrella for issues of national policy with respect to geographic information. The term was coined in the early 1990s, and sanctioned by a Presidential Executive Order in early 1994. Major efforts under the NSDI include the development of data dissemination mechanisms such as the National Geospatial Data Clearinghouse; standards for data formats and data description (metadata); identification of the most valuable geospatial data sets (defined as those most useful by the largest number and most diverse set of users); and development of standard terminology. Much of this activity can be viewed at *www.fgdc.gov*, the Web site of the Federal Geographic Data Committee.

National policy is still deficient or inadequate in many areas relevant to geographic information, and this UCGIS research area is defined with the objective of helping to fill that gap. Intellectual property issues are an area of very active debate, where traditions of fair use and distribution at cost of reproduction run up against new efforts to benefit economically from digital databases. Protection of individual privacy is an issue at the national level, and is seriously challenged by many developments in GIS.

2.5 Extensions to geographic representations

Humanity has accumulated a vast amount of knowledge of the distribution of features over the surface of the Earth, but very little of that vast store is accessible for manipulation and analysis through the medium of GIS. In part, this is because so little has been converted to digital form, given the expense. But in part it is due to the limitations imposed by GIS data models, which favor particular types of knowledge about the Earth's surface over others. GIS data models have developed largely for the purposes of digitizing the contents of paper maps, and it has proven difficult to implement models that go significantly beyond what can be represented on a sheet of paper.

The 'map metaphor' limits our ability to represent geographic phenomena in at least six ways. The map is two-dimensional, and very little progress has been made in extending GIS to three spatial dimensions. It is static, and much work in GIS also ignores the temporal dimension. Maps are flat, and we have limited ability to process data on the curved surface of the Earth. Maps show information at a single level of resolution, and GIS have not been extended to handling hierarchies of scales. Maps show a uniform level of resolution, and there are few capabilities in GIS for storing patchworks of different quality. Finally, maps present knowledge as if it were exact; much recent research effort has gone into recording uncertainty in spatial databases.

2.6 Cognition of geographic information

The methods used by GIS to handle information are clearly different from those used by the human mind, and this is reflected in the very great efforts needed to learn and master GIS. The term *naïve geography* has been coined to describe structures grounded in human cognition that differ distinctly from their formal equivalents. This gap between human cognition and GIS will have to be overcome if GIS are ever to be regarded by the general public as 'easy to use', or introduced to young children. The GIS user interface is where human cognition and database come together, and research into cognition speaks directly to user interface design. But the importance of this research area also addresses such areas as visualization, the interpretation of plain-language commands, and the recording of geographic information by human observers.

Research into cognitive models of geographic phenomena is being pursued in a number of centers, and the COSIT series of conferences now provides an international forum for sharing reports of progress (Hirtle and Frank, 1997). Much more effort will be needed, however, before there can be a truly smooth interface between the human mind and GIS.

2.7 Scale

Scale is a concept inherited from the paper map, where it is most often defined as the representative fraction, or the ratio between distance on the map and the corresponding distance on the ground. To a scientist, it also means the level of detail in data, as measured by resolution, and also the area covered, or the data's geographic extent. Sorting out the differences between these and other uses of the word has proven difficult (Lam and Quattrochi, 1992). Moreover, the accurate description of level of geographic detail in a data set has become of great importance in the effective definition and functioning of metadata.

Much more research needs to be done on the relationship between level of geographic detail and related concepts, and their manipulation and management in GIS. We need to know more about the costs of working with data at the wrong scale, about how to automate methods of scale change, about automated update of scale measures when data are transformed, about the construction of multi-scale databases, and about methods of working with data at multiple scales, particularly when scale varies within a single data set. The NSDI is based on a concept of patchwork, with national databases constructed from pieces provided by local agencies at different levels of resolution; but we do not yet know how to handle or analyze such data.

2.8 Uncertainty in geographic data and GIS-based analyses

Uncertainty in geographic data can be defined as the difference between contents, and what the contents are believed to represent. When the contents are believed to represent the truth, then terms such as *error* and *accuracy* can be used, but in many cases it is difficult to define a truth. Research on uncertainty focuses on its sources, on its description and modeling, on its visualization, and on methods for predicting its effects on the outputs of analysis, given knowledge of uncertainty in inputs. Research relies heavily on two distinct traditions: that of statistics and probability on the one hand, and that of fuzzy sets on the other.

Substantial progress has been made in the past 10 years, and much is now known about the nature of uncertainty in geographic data. A number of models have been proposed, and methods of propagation have been developed (Heuvelink, 1998). However, much of this work is based in spatial statistics, and its effective use requires a fairly sophisticated level of understanding of statistical theory. Future research will have to focus on making these methods more accessible to general users, by developing methods of visualization that communicate knowledge of uncertainty using intuitive metaphors, and by developing ways of describing uncertainty in metadata without recourse to sophisticated understanding.

2.9 Spatial analysis in a GIS environment

Techniques of spatial analysis support the manipulation of data in order to summarize; to reveal what may not otherwise be apparent to the user; to test goodness of fit to models; to identify anomalies and other exceptions to general trends; to find patterns that suggest generalizations and theories; and to support decisions. This is a very broad set of objectives, and the set of methods of spatial analysis is similarly broad, as a glance at any of the standard texts will confirm (see, for example, Bailey and Gatrell, 1995). GIS provides a convenient and powerful framework for implementing methods of spatial analysis in computational environments.

In turn, the widespread adoption of GIS has led to calls for new methods of spatial analysis that are more appropriate to its users. These include methods that are intuitive, reinforcing what is already clear to a user with rigorous statistical tests or other procedures; methods that are able to scan very large amounts of data in search of patterns and anomalies; methods that are exploratory, massaging data to reveal possible generalizations; and methods that are local in focus, emphasizing the propensity for generalizations about geographic phenomena to vary over space. Many other possible directions for development are outlined in the UCGIS documents.

2.10 GIS and society

In recent years much has been written about the social context of GIS, and the values that are implicit in the use of GIS by various individuals, agencies, and groups (Pickles, 1995). For example, widespread adoption of GIS by government agencies has led to the suggestion that its use serves to reinforce the power of the elite, rather than to balance that power by empowering marginalized groups. GIS use raises ethical questions, and is increasingly implicated in legal disputes. It has the potential to be used for surveillance, and to invade privacy in other ways.

Research into GIS and society seeks to illuminate some of these issues, through case studies, reflection on the nature of GIS practice, and other methods. Such attention may help to improve GIS practice in the long run, by making practitioners more sensitive to the nature of what they do. It may lead to better ways of representing the views of individuals and groups, especially when these views are expressed in ways that are not easily accommodated in traditional GIS. Such issues occur, for example, in debates about land claims that cross cultural and linguistic divides.

3. OTHER PERSPECTIVES AND GRAND CHALLENGES

As noted earlier, the UCGIS research agenda is a consensus view of the U.S. research community on the appropriate topics for research. It has undergone much discussion since it was first formulated, but the 10-topic structure remains intact. Perhaps the only significant suggestion is that it misses the importance of visualization, by not identifying an area under that heading. On the other hand, visualization is clearly important in many areas of the agenda, including cognition, uncertainty, and representation.

The term *priorities* was used during the initial discussions in 1996, but opinion during the 1998 Annual Assembly seemed to favor *challenges* instead. This reflects a view held quite broadly within the scientific community that it should be possible to identify *grand challenges* in a discipline, and that the existence of grand challenges is somehow a test of the depth or stature of a discipline. If so, what are the grand challenges of GIScience? What would one say to an Albert Einstein or a Stephen Hawking to try to convince them of the significance of GIScience? What is there in GIScience (or Geomatics if one prefers that term) to challenge the truly great minds? What would be suitable topics for a Nobel Prize in GIScience, if one existed?

There has been no discussion of this issue within the GIScience community, and any suggestions are therefore personal, and not the result of any process of consensus-building. However, I would like to suggest four, all of which I believe satisfy the test of a grand challenge to some degree.

3.1 The challenge of representation

Although it was expressed earlier in terms of the map metaphor, it seems to me that the challenge of representation in GIScience is of sufficient magnitude to rate as grand. The geographical world is infinitely complex, being the result of the distribution of almost 100 distinct chemical species, at densities of order 10^{23} molecules per cubic centimeter. Magnetic, electrostatic, and gravitational fields vary continuously at geographical scales, as do such abstracted properties as temperature, pressure, pH, and fluid velocity. Thus any model or representation of real geographical variation must be an approximation, generalization, or abstraction. Humans have devoted centuries to developing useful ways of characterizing this variation, in terms of the attributes of homogeneous objects of finite size, mathematical functions over finite domains, and many other methods. In the digital world, all such methods must ultimately be constructed from some permutation of two symbols or states: 0 and 1. Moreover, approximations must be expressed in a limited number of digits, since computer storage space is limited, despite enormous advances in the past few years. The grand challenge for GIScience is *to find useful ways of representing the infinite complexity of the real geographical world in the absurdly crude and limited space of a digital store.* To be successful, representations must be intelligible to all, following generally-agreed standards of format, coding, and generalization; must use only the binary alphabet; must be useful, having successful application in some range of significant applications; must be efficient; and must include representation of both spatial and temporal dimensions.

3.2 The challenge of uncertainty

As noted earlier, uncertainty can be defined as what is missing in a representation, or the differences between a representation and the real phenomena it is understood to represent. Because that understanding can vary from one person to another, uncertainty is an attribute both of the data and of the individual making the assessment, and can change as data pass from one custodian to another, depending on whether a consistent understanding is shared between them. The grand challenge of uncertainty in geographic information is *to find useful ways of summarizing and characterizing the differences between representations and real phenomena, and communicating such summaries and characterizations to others.*

3.3 The challenge of cognition

Methods for describing geographical phenomena have evolved over centuries, and principles of spatial cognition are learned very early in life as fundamental parts of our cognitive structures and processes. The digital computer is a much more recent phenomenon, and although parallels are often drawn between the human brain and the digital computer, in reality their ontology and methods of expressing knowledge are enormously different. In the GIS case, for example, there were no cartographic or other precursors to the triangulated irregular network (TIN), although that structure is widely used as a method for representing terrain in a GIS. Earlier it was noted that human ways of learning, thinking, and reasoning about geographic phenomena are very different from those of GIS. The grand challenge of cognition in GIScience is *to achieve smooth integration and transition between cognitive and computational representations of geographic information.* The practical significance of this challenge, in the form of ease of use of digital technology, was described earlier.

3.4 The challenge of simulation

GIS algorithms and procedures need to be tested, so there is often a need in GIS research for data sets that can be regarded as typical, and from which generalizations can be made. For example, empirical testing of the computational complexity of an algorithm requires that it be run on problems of varying sizes, and for the results to hold true generally it is desirable that the data used be in some sense generic. We know, however, that the Earth's surface exhibits enormous variation, and it seems impossible therefore to believe that any data set can be truly generic.

This issue has a long history, and in certain domains it is accepted that the results of simulation bear striking resemblance to real phenomena. Benoit Mandelbrot titled his second book *The Fractal Geometry of Nature* (Mandelbrot, 1982) based on convincing illustrations that fractional Brownian processes could provide realistic simulations of certain types of real landscape, and fractal simulation has now been carried to a fine art (see, for example, Barnsley, 1993). The human eye is clearly skilled at detecting differences between simulations and the real thing, and the ability to simulate requires an advanced knowledge of the processes that have formed the real landscape—knowledge that is beyond our current abilities in many areas of Geography. Thus the grand challenge of simulation, or GIScience's version of the Turing test, is *to create simulations of geographical phenomena and landscapes in a digital computer that are indistinguishable from their real counterparts.*

3.5 One more challenge

Consider a street centerline database, containing locations, attributes, and connections of a representation of a real street network. Now suppose that the location of one intersection has been re-measured, and determined to be substantially displaced. Because of the interdependencies that exist in any such representation, it is impossible to update the location of the intersection without also making changes in the locations of other parts of the same features, and perhaps also of neighboring features. Update has become a major problem for GIS databases, and a substantial industry has grown up around the problems encountered when it becomes possible to replace parts of a database with improved parts. In the case of the intersection, Figure 1 shows the original network (Figure 1a), relocation of adjacent links keeping them straight (Figure 1b), and curving the links (Figure 1c). A third option would involve shifting the entire network. The first two are unacceptable because they create local geometry which no longer match reality; the third is unacceptable because of the mismatches it creates with adjacent networks. Which of the three options one selects depends essentially on what one believes about interdependencies of positions in the database.

In essence, the problem identified here is due to the structure of the database, which represents features in locations that have been determined by a complex process, but retains no information on that process. If one knew, for example, that the database had been built by making independent measurements of intersection locations, and then connecting intersections with straight lines, then Figure 1b would represent the best solution. If one knew that positions had been determined by photogrammetry from a single image, and that the error was due to misregistration, then shifting the entire database would be appropriate.

This problem is well known in surveying, and has been studied for many years, with the result that a substantial body of theory has accumulated. The solution to it lies in restructuring our entire approach to database construction, focusing not on derived positions but on the independent measurements that led to those derivations. In such a structure, a change in one measurement would be used to update all derived measurements. This solution is not one that would occur to an industry bent on building a GIS to represent the contents of maps, or one that paid no attention to error and uncertainty in data. In essence, the current design of GIS is founded on the belief that it is possible to determine position exactly on the Earth's surface, and thus focuses on the storage of that position, rather than on the measurements that supported its determination. From a computational perspective, positions in such a system are a *view*, but a view does not necessarily coincide with content. The challenge in this case is *to design a computational environment based on independent measurements rather than derived positions, thus solving the problem of incremental update of spatial databases.*

4. APPLICATIONS OF GISCIENCE

Few would dispute the contention that GIS is driven by its applications, and that the growth in the GIS software industry and in interest in GIS over the past two decades has been due largely to its immense variety of applications, and the very large number of problems amenable to spatially-explicit problem-solving with GIS.

Looking back, it seems that GIS applications have arrived in three waves:

1. Applications in urban planning and resource management that drove the early developments of the 1960s and 1970s, culminating with the first round of adoption of commercial systems in the 1980s. In addition, military applications of remote sensing and GIS drove much of the early development.
2. Applications to the management of the distributed assets of utility companies, including water, electricity, gas, telephone, and cable TV, leading to widespread adoption by major corporations in the 1980s and 1990s, under the rubric of automated mapping/facilities management (AM/FM); and related applications in logistics, including parcel delivery and transportation.
3. Applications to banking, insurance, and marketing, which began to develop in the 1990s under the rubric of business geographics and geodemographics, together with applications in health and human services.

If we accept that interest in GIS has led to the emergence of a scientific enterprise, termed Geomatics or GIScience, then an entirely new range of applications are suggested based on science rather than on technology and tools. For example, the improved theories, principles, and concepts called for earlier in this paper should lead to major advances in interoperability between technologies and data, and to much easier and simpler education and training in GIS. Easier use should lead also to a more informed citizenry, and one that is more empowered to learn, reason, and make decisions about the geographical world. Geographical data should be easier to find and retrieve from the distributed storehouse of the Internet, and easier to manipulate in interesting ways.

5. CONCLUSION

Within the U.S. research community at least, the term GIScience seems to be increasingly accepted as a label for research related to and in support of the geographic information technologies. It attempts to provide a clear set of principles and theories to frame the tools, and to investigate topics that are likely to impact the development of the tools in the future. Several sources now provide outlines of its research agenda. In this paper I have tried to add to the consensus represented by the research agenda of the UCGIS by suggesting a few topics that seem to meet the requirements of grand challenges, and have argued that the existence of such challenges is an important test of a discipline.

As we enter the new millennium, it seems that GIScience is alive and well, and even flourishing. There appears no particular reason to expect the Y2K bug to impact GIS any more than any other area of electronic data processing; in fact, it may impact GIS less because of the general paucity of transaction-based applications. On the other hand the spatio-temporal frame which the millennium celebrates, through the planned celebrations at Greenwich in particular, provides the defining characteristic of GIS, although more from its spatial than its temporal dimensions.

Nevertheless, there is perhaps one reason why the GIScience community should pay particular attention to the millennium. As noted earlier, the cartographic tradition of flattening the Earth is alive and well in its digital successors. Although we deal in GIScience with the curved surface of the Earth, we are remarkably reticent to adopt its technical accoutrements: geographic coordinates instead of coordinates on projections; spatial analysis techniques for the sphere and ellipsoid instead of the plane; data models that tile the curved surface; and visualizations of the Earth as it appears from space. A concerted effort to develop GIS for the globe would be a fitting millennial contribution from the research community.

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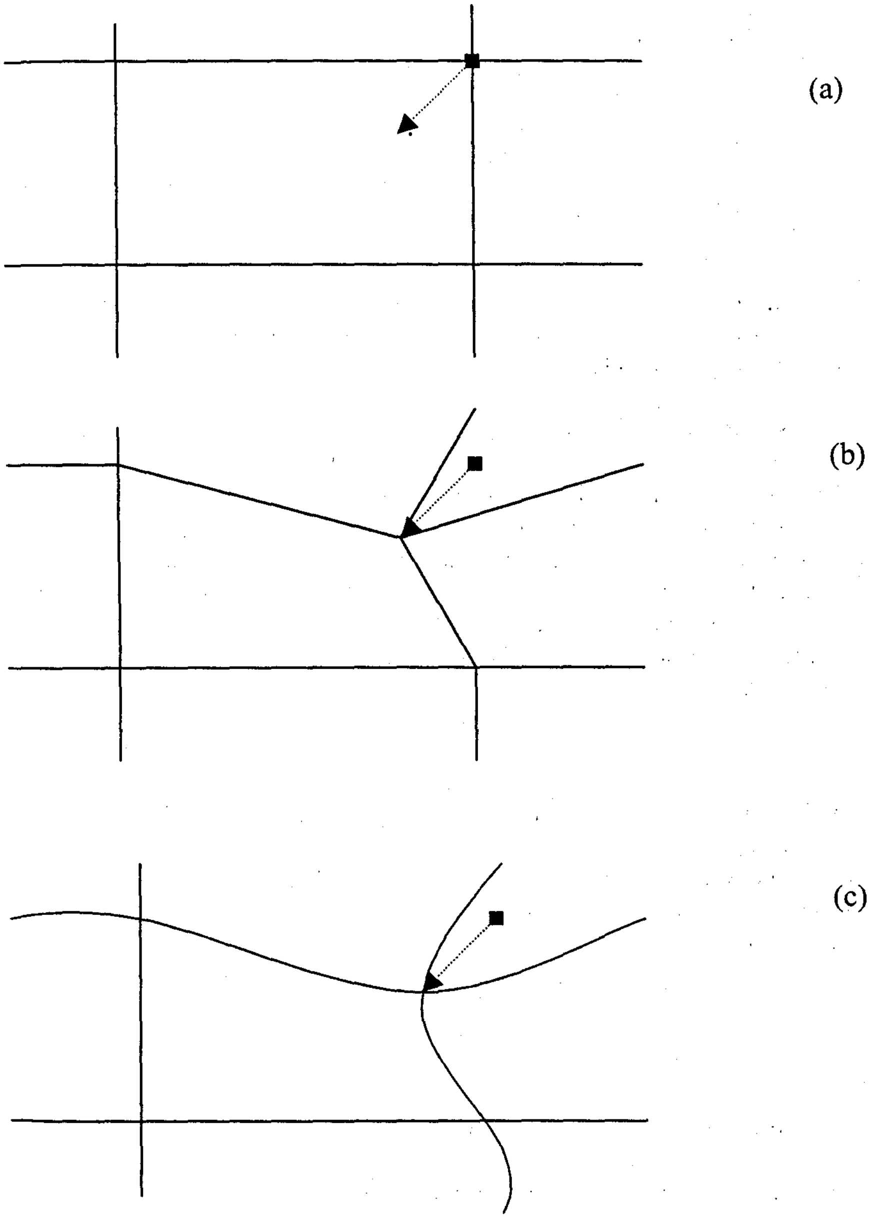

Figure 1. Options For Updating A Network Based On A Relocated Intersection

In Figure 1b, the immediately adjacent links are kept straight, creating unreasonable intersection angles. In Figure 1c, the intersection angles are better preserved but the links are no longer straight. A third option is to shift the