# CHALLENGES IN SPATIAL ANALYSIS

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## 1. INTRODUCTION

This is a time of unprecedented opportunity for spatial analysis. More people than ever have access to the Global Positioning System for direct measurement of location on the Earth's surface; to the products of high-resolution remote-sensing satellites; and to the manipulative power of geographic information systems (GIS). Some of these technologies are encountered in everyday life, through sites such as Google Earth (earth.google.com), Google Maps (maps.google.com), and Microsoft Windows Live Local (live.local.com), and through the widespread use of in-vehicle navigation systems. Several academic disciplines are recording a *spatial turn*, a new and in some cases renewed interest in space and location as a framework for analysis, understanding, and presentation of results. A recent publication (National Research Council, 2006) has defined and explored *spatial thinking* as a paradigm for primary and secondary education, and projects have been funded around the world to advance *spatial literacy* (e.g., www.spatial-literacy.org).

At the same time the field faces substantial challenges, as it attempts to take advantage of these new opportunities. This chapter addresses four: the challenge raised by the continuing rapid advance in computing and networking technology; the challenge of addressing the temporal dimension through the analysis of dynamic phenomena; the challenge posed by the immense popularity of Web sites that offer rudimentary forms of spatial analysis to a user community that has little or no formal educational background in this area; and the challenge of formulating a new philosophy of science that reflects the actual conditions under which spatial analysis is used in today's research and problem-solving environments.

The four topics by no means exhaust the full set of issues facing the field. Many readers will have their own ideas, and the three chapters on the future of spatial analysis that follow include discussions of additional issues. Meanwhile, the four considered in this chapter are very much a personal list, and reflect the author's own interests and concerns at this point in the long history of spatial analytic methods.

## 2. COMPUTING AND NETWORKING TECHNOLOGY

In the early 1990s a substantial literature accumulated on the opportunities offered by GIS. In 1988 the U.S. National Science Foundation had established the National Center for Geographic Information and Analysis (NCGIA) at three sites: the University of California, Santa Barbara; the State University of New York at Buffalo; and the

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University of Maine. One of NCGIA's objectives was to advance the use of GIS across the sciences, as a platform for spatial analysis, so it was considered important to assess progress to date, and to identify and remove impediments to the greater use of spatial analysis. NCGIA organized a specialist meeting on the topic that eventually led to a book (Fotheringham and Rogerson, 1994), and several additional papers appeared (Anselin and Getis, 1992; Burrough, 1990; Ding and Fotheringham, 1992; Goodchild, 1987; Goodchild *et al.*, 1992; Openshaw, 1990; and for a later perspective see Goodchild and Longley, 1999).

Underlying this spate of funding and writing was the simple premise that GIS provided an ideal means of implementing the known techniques of spatial analysis, as well as techniques that might be developed in the future. A single package, if sufficiently sophisticated, could offer easy and largely painless access to an abundance of robust, scientifically sound techniques for analyzing and visualizing spatial data. The results of each stage of analysis could be fed into further stages, and data could be managed within a single environment that recognized a range of data formats. Comparisons were frequently drawn with the statistical packages (e.g., Goodchild, 1987), which similarly offered easy access to a multitude of statistical techniques, along with the necessary housekeeping functions.

At the time, each GIS software product was organized into a single, monolithic package. In the 1980s such packages were typically installed on minicomputers such as the VAX or Prime, but in the late 1980s the transition to personal Unix workstations and later to the PC and Mac had opened the possibility of an entirely individualized toolbox installed on the researcher's desk. GIS was likened to a butler – an intelligent assistant working with the user to solve problems, knowing the foibles and preferences of the user, and taking on those tasks that the user found too complex, tedious, time-consuming, or inaccurate if performed by hand. Abler (1987) hailed GIS as geography's equivalent of the microscope or the telescope, a powerful tool that allowed researchers to gain insights that were simply impossible with the normal senses and intuition.

From this perspective, the power of GIS would be judged simply by the proportion of known techniques of spatial analysis that it supported, by the accuracy with which it implemented each method, and by the extent to which it prevented misuse and misinterpretation of results. There were many complaints about this time regarding the success of GIS against these objectives. Commercial software developers were seen as insufficiently interested in supporting advanced spatial analysis, being content instead to direct their efforts at satisfying the needs of their more wealthy corporate and agency customers, whose interests tended to be more in data management and inventory. GIS designers failed to ground their products in sound theory, preferring intuitive terms and explanations over formal and mathematical ones. Because of this lack of formal grounding, each vendor tended to adopt its own terms, formats, and structures, leading to endless proliferation and an apparently insurmountable lack of interoperability.

It was in this context that the Web appeared on the scene, and the Internet emerged as the dominant and indeed quickly the only network for computer communication. Since 1993 and the release of Mosaic the impact of communications technology has been so profound as to change the entire landscape of GIS and spatial analysis. Sui and Goodchild (2001) have argued that the metaphor of the butler is no longer appropriate – instead, GIS technology now constitutes a medium through which people communicate what they know about the Earth's surface that is comparable to traditional media such as print, radio, and television. As such, its issues are dramatically different from those of earlier decades. Bandwidth, interoperability, and metadata have largely replaced computing speed, storage capacity, and the sophistication of desktop software as major concerns of GIS users. Even the most sophisticated of users no longer program, relying instead on the incredibly abundant resources of the Web, easy mechanisms for sharing code, and new forms of software architecture. The following three sections explore some of these issues, and their implications for spatial analysis.

## 2.1 Server GIS

In the client-server computing paradigm that underlies the Web, the user or client's hardware and software are comparatively simple or *thin*, and most actual computation occurs remotely on a more powerful server. In the extreme, the user needs only a Web browser such as Microsoft Explorer or Netscape. Instead of installing a *thick* piece of software, such as a GIS package, the user obtains many if not all of its services from a remote server. For example, the task of finding the optimum route from an origin to a destination through a street network, the task performed by many Web sites such as mapquest.com, no longer requires the user to obtain a powerful GIS and the necessary database representing roads and streets, and to mount both on his or her desktop machine, since the same service can be obtained free from the server. The user need only specify the origin and destination to the server using a Web browser; the results are then sent back from the server and displayed locally using the same Web browser.

In principle all GIS functions and all types of spatial analysis could be organized in this way. Instead of installing and operating their own software, researchers could send data to sites where sophisticated forms of spatial analysis were performed. Researchers developing new forms of spatial analysis would find it far easier to offer their techniques as Web services than to engage in the time-consuming distribution of software, and users would benefit by not having to spend time obtaining, installing, and maintaining their own copies.

Server GIS is now common among public agencies interested in providing public access to their spatial data, along with simple capabilities for query and visual display. Many local governments provide access to their land-ownership and property taxation databases in this way, allowing users to query details of their own and other properties, using a map interface.

In practice, however, server GIS has had a limited impact to date, particularly for more sophisticated analysis, for a number of reasons:

- There is no consensus on the appropriate business model for server GIS. Desktop GIS software generates income for its developers through sales and licensing, providing a healthy income stream, and developers of new methods of spatial analysis have sometimes used this same approach. Users of server GIS typically expect services to be provided free, leaving the providers of such services to generate income through advertising and the licensing of services to third parties. Routing services, for example, can be found embedded in the Web sites of on-line travel agencies and real-estate companies, presumably at some cost to them. Moreover, the software for server GIS tends to be more expensive per copy than conventional desktop GIS software (although open-source packages are available, e.g., mapserver.gis.umn.edu).
- Server GIS is most effective when the volume of data that needs to be input by the user is limited, and when the data needed are common to a large number of users and applications. A routing service, for example, requires only an origin and destination, and uses a generic database of streets and roads stored at the server. Moreover, such databases change frequently, and there are enormous economies of scale if all users can rely on a single version. Geocoding or address matching, the task of converting street addresses to coordinates, has become a popular function for server GIS for the same reason.
- Lack of interoperability continues to be an issue for server GIS. There are no standards for the description of services, though several *geo-portals* now provide limited directories (Maguire and Longley, 2005; Goodchild, Fu, and Rich, in press). Extensive reformatting may be needed to make data readable by remote services, and the results returned may similarly need to be reformatted to be useful locally.

The choice between local and server-based computing is a complex one, and developers and implementers of spatial-analytic routines will need to consider the options carefully. However, it is clear that the nature of computing is changing, as many services move to a central, server-based model.

## 2.2 Process scripts

Research tends to proceed in stages, as problems are formulated, data are collected and checked, analysis is performed, and results are scrutinized. Each stage feeds forward to the next, and also back to the previous stages, as projects are rethought and as hypotheses are tested and modified. By the time the project is finally completed, the investigator may well have lost track of some of the stages, and may find it difficult to provide the necessary details in publications and reports. Somewhat paradoxically, the research community has invested heavily in the infrastructure to create and share data, and in the software to process them, but has not made similar investments in the techniques for management of the research process. The problem grows more severe as research becomes more collaborative, with many participants who may or may not communicate in person, and as the tools of research become more complex.

Against this background it is not surprising that many vendors of GIS and spatial-analytic packages have created *macro*- or *scripting* languages that allow researchers to express complex analyses as sequences of operations, and to store, manage, and execute such sequences as simple commands. A script in digital form is immediately more easily shared, managed, and documented than its equivalent in the jotted and invariably incomplete hand-notes of the researcher. Modern scripting languages allow complex hierarchical structures, since a single line in a script can invoke other scripts and programs, and allow sequences of operations to be repeated many times in such applications as Monte Carlo simulation.

However, the design of an appropriate scripting language is a very sophisticated task, requiring a high level of knowledge of the needs of the research community, across many disciplines and domains. Simple scripting languages merely allow the user to invoke any of the commands of the package, but more sophisticated languages imply a recognition of the fundamental elements from which complex spatial analyses are built. If the granularity of the scripting language is too coarse, researchers will find it too difficult to express the full range of applications – and if it is too detailed, the script will be unnecessarily long.

The work of Tomlin (1990) provided the first successful effort at a generic scripting language for GIS, albeit only for congruent layers of raster data. The language was adopted by several packages, and several extensions were made. Van Deursen (1995) analyzed the operations required to support dynamic modeling in a raster environment, including the implementation of finite-difference models, in what became the scripting language for PCRaster (pcraster.geo.uu.nl), a raster-based package heavily oriented towards environmental modeling. Takeyama and Couclelis (1997) described a sophisticated language for the manipulation of pairs of raster cells, providing support for the analysis of spatial interactions. More broadly, all of these approaches are strongly related to the languages developed in image processing, or *image algebras*.

To date, however, there have been no comparably ambitious efforts to devise languages for vector data, or for the broader framework that spans both discrete objects and continuous fields. Dynamic GIS that addresses both space and time also lacks comprehensive scripting languages. The effectiveness of future spatial analysis clearly depends on the community's ability to devise simple yet comprehensive languages that can be used to describe and share computational methods. In the past, mathematics provided an adequate language, and models were effectively shared using algebraic representation, through the pages of learned journals and books. But today's computational environments present a somewhat different problem, since the language of mathematics lies too far from actual implementation, and cannot readily be used to express the entire algorithmic basis of spatial analysis.

### 2.3 Interchangeable software components

Early computer software was comprised of *programs*, integrated pieces of software that performed well-defined functions. Early GIS developed in this context, and by the early

1990s a fully featured GIS such as ESRI's ARC/INFO included millions of lines of code, all designed to be compiled and executed together to provide a single, integrated computing environment.

This approach to software was both redundant, in the sense that large amounts of code might never be executed by a given user, whose interests might focus only on a small number of functions; and costly, in the sense that it was difficult for programmers to pull pieces of code out of one package to be reused in another. Even today, the average user of a package such as Microsoft Word will likely never have invoked many of the functions in this very large and complex package.

Several attempts to break out of this mold were made in the 1980s and 1990s. One of the more successful was the concept of a *subroutine library*, a collection of standard routines that could be *called* by programs, avoiding the need for repetitive reprogramming. Subroutine libraries became common in areas such as statistics, since they allowed comparatively sophisticated users to develop new programs quickly, relying on standard subroutines for many of the program's functions. The idea was difficult to implement for less sophisticated users, however, since it required each to possess a substantial knowledge of programming.

Contemporary approaches to software emphasize a rather different approach, in which sections of reusable code, or *components*, can be freely combined during the execution of a program. Standards have been developed by vendors such as Microsoft that allow compliant components to be freely linked and executed. Ungerer and Goodchild (2002) describe one such application, in which ESRI's ArcGIS and Microsoft's Excel have been combined to solve a standard problem in areal interpolation (Goodchild, Anselin, and Deichmann, 1993). Functions that are native to the GIS, such as polygon overlay, are obtained from ArcGIS, while operations on tables, such as matrix multiplication, are obtained from Excel. The entire analysis is invoked through commands written in Visual Basic, a form of scripting language, though other general scripting languages such as Python might also be used. Both packages are compliant with the Microsoft COM standard, allowing the components that form the building blocks of each to be freely combined and executed.

Approaches such as these are breaking down the barriers that previously existed between different types of software – in this case, ArcGIS and Excel – and allowing much more flexible forms of analysis. They invite an entirely new approach to software design, in which fundamental components with widespread application are combined to meet the needs of specific applications. They also call for answers to a fundamental question: what are the basic building blocks of spatial analytic software, and to what extent are the operations invoked by each form of analysis common to more than one form? Perhaps they will lead eventually to a new approach to teaching in spatial analysis, in which these fundamental building blocks are the elements of a course, rather than the analytic methods themselves.

## 3. TIME AND DYNAMICS

Many authors have commented on the generally static nature of GIS, and the difficulty of representing time and dynamic phenomena. Most attribute this to the legacy of the paper map, which inevitably emphasizes those aspects of the Earth's surface that remain relatively static, over such dynamic phenomena as events, transactions, and flows. Several comprehensive reviews have appeared, and much progress has been made in building spatial databases that include time (Langran, 1993; Peuquet, 1999, 2001, 2002).

This same emphasis on the static is evident in the toolkit of spatial analysis, with its focus on cross-sectional data. In part this is due to the difficulty of creating and acquiring longitudinal data: to the administrative difficulties that statistical agencies face in funding and maintaining data-collection programs through time; to the changing nature of the Earth's surface, and the impact that this has on data-collection procedures and the definitions of reporting zones; and to the changing nature of human society, and its notoriously short attention span. Efforts such as the National Historic GIS project (www.nhgis.org) have attempted to overcome these difficulties, building systems that allow users to construct longitudinal series from the census for example, but they remain comparatively few and far between.

While much progress has been made, the analysis of spatio-temporal data remains a comparatively underexplored area, and a source of substantial challenges for the community. The next two subsections address two of these in greater detail.

## 3.1 Fundamental laws

Much of the nature of GIS and many of the architectural choices that have been made over the past several decades are ultimately attributable to the nature of the data themselves – the ways in which spatial data are special. Anselin (1989) has identified two general characteristics, and Goodchild (2003) has discussed several more.

Spatial dependence describes the widely observed tendency for the variance of spatial data to increase with distance. To paraphrase Tobler (1970), nearby things are more similar than distant things, a principle that has become known as the First Law of Geography (Sui, 2004). All of the methods used to represent geographic phenomena in GIS are to some extent reliant on the validity of this principle. For example, there would be no value in representing topography with isolines if elevation did not vary smoothly, and there would be no value in aggregating areas into contiguous regions if the latter could not be designed with relatively low within-region variance.

Anselin's second principle is spatial heterogeneity, the tendency for the Earth's surface to exhibit spatial non-stationarity. All of the various techniques developed over the past two decades for *local* spatial analysis are based on this principle, since they attempt to summarize what is true locally, rather than what is true globally. The Geographically Weighted Regression of Fotheringham, Brunsdon, and Charlton (2002) falls into this category, as do the LISA technique of Anselin (1995) and the local statistics of Getis and Ord (1992).

If such principles are generally true of spatial data, and are useful in guiding the development of computational systems, then one might reasonably ask whether similar principles exist for spatio-temporal data, and whether such principles might usefully inform the development of a more dynamic approach to GIS and spatial analysis. What is the spatio-temporal equivalent of Tobler's First Law, for example? Does spatial heterogeneity apply also in time? What relationships exist between the parameters of spatio-temporal and spatial dependence and heterogeneity? Are other general principles of spatio-temporal phenomena waiting to be discovered?

### 3.2 Dynamic form

Spatial dependence and spatial heterogeneity are both properties of how the Earth's surface *looks*, capturing aspects of its form. Studies of form have a long history in science, but have given way in the long term to a desire to understand process – to understand how systems *work*, and the effects of human intervention. In geomorphology, for example, many scientists of the 19th and early 20th centuries were content to describe landforms, devising elaborate systems of morphological classification, and only later did interest develop in understanding how landforms came to be, and the processes that left such characteristic footprints on the surface. Today, of course, such studies of form are largely discredited, as they are in many other disciplines.

Because of its essentially static legacy, much GIS analysis has focused on form, and has been criticized for doing so. It is comparatively difficult to tease insights into process from cross-sectional form, though it is perhaps sometimes possible to eliminate false hypotheses about process. GIS has been accused of being the last manifestation of the quantitative revolution that occurred in geography in the 1960s, when Bunge (1966) and others attempted to draw insights from the similarity of forms found on the human and physical landscapes (see, for example, the critique of Taylor, 1990).

Very little is known, however, about the characteristic forms that may exist in spatio-temporal phenomena. Hagerstrand (1970) and others have examined the movements of individuals in space and time using three-dimensional displays, in which the two spatial dimensions form the horizontal plane and time forms the vertical axis. Much of this work focuses on similarities that may exist in the forms of such tracks, and the implications they may have for process. We know from the work of many researchers (e.g., Janelle and Goodchild, 1983) that different social conditions lead to dramatically distinct track forms, as for example in the differences between the daily tracks of single mothers, with their orientations to both workplace and daycare, and the tracks of workers in families in which only one of two adults works.

The development of greater support for time in GIS may lead to many other recognizable patterns in spatio-temporal data, and to a rebirth of interest in the study of spatio-temporal form. A new generation of analytic techniques is needed that extracts meaningful pattern from the mass of tracks displayed in the visualizations of Kwan and Lee (2004) and others, and links such patterns to hypotheses about process.

## 4. SPATIAL LITERACY

In the past few years a remarkable series of Web sites have brought the sophisticated functions of GIS and spatial analysis much closer to the general public. While effective use of GIS requires extensive training, and in many cases advanced work at the undergraduate level, technologies such as Google Earth have given every citizen with a computer and a high-speed Internet connection access to many of the data sets and computational functions of GIS, and in some cases have even exposed the more sophisticated functions of spatial analysis. For example, anyone requesting driving directions from one of these sites receives answers that result from the execution of a complex algorithm that was previously the reserve of operations researchers and specialists in spatial optimization.

The methods of cartography and related disciplines are complex, and it is no surprise therefore that sophisticated tools in naïve hands can produce mistakes. A suitable example concerns the Greenwich meridian, and its position when displayed in Google Earth. Many users of this site have noted that the zero of longitude misses the Greenwich Observatory by approximately 100m, and have posted comments, some of which conclude that a serious mistake has been made by Google, and by extension that the georegistration of imagery on the site is poor. In reality, the WGS84 (World Geodetic System of 1984) datum, now widely adopted around the world, does not place the Greenwich Observatory at exactly zero longitude, despite the international treaty that established it there in 1884 – and the position shown in Google Earth appears to be correct to within a few meters.

Although their support for spatial analysis is extremely limited, these sites have clearly provided the general public with access to a rich resource, and thousands of people have been empowered to create their own applications. The recent publication *Mapping Hacks* (Erle, Gibson, and Walsh, 2005) describes many fascinating examples, but contains not a single reference to the cartographic literature. At the same time students who have endured many hours of lectures and lab exercises to become competent in GIS may be frustrated to realize that a child of ten can create a computationally complex fly-by using Google Earth in a few minutes.

It seems clear that in part as a result of these developments the demand for basic knowledge of the principles of spatial analysis, GIS, geography, cartography, and related fields – for basic *spatial literacy* -- is perhaps two or more orders of magnitude out of alignment with the supply. Education in these topics cannot be confined to a few advanced undergraduates, and to campuses lucky enough to have faculty interest, if it is to be accessible to the numbers of people now exposed to and enthusiastically adopting these tools. In this respect, spatial analysis faces an unprecedented challenge, to make itself known to a much larger community than previously.

There are several ways in which such a challenge might be met, by concerted effort on the part of the spatial-analysis community. One is to bring spatial literacy into the general-education or core curriculum of institutions of higher education, making its material accessible and eligible for credit for the vast majority of undergraduates. Courses in other kinds of literacy are already available in this form; the argument needs to be made that familiarity with spatial analysis and GIS represents another, and arguably a more powerful form of literacy that should be part of the education of every citizen. Another strategy would be to develop a larger and more visible set of courses in the informal education sector, making spatial literacy part of on-line and certificate programs, and exposing its contents through libraries, museums, and other institutions. A third is to work to introduce spatial literacy earlier in the educational hierarchy, in high school and even elementary school. Valiant efforts have been made in this direction in the past, but they remain minimal in comparison with the size of the primary and secondary sectors, and there is much confusion about where such material might fit in the already stove-piped curriculum.

## 5. BEYOND TRADITIONAL PRACTICE IN SCIENCE

When Harvey wrote his well-known and highly influential *Explanation in Geography* (Harvey, 1969) the dominant form of scientific practice centered on the individual investigator, whose methods followed a set of well-defined principles. For example, every experiment was to be reported in sufficient detail to allow its replication by another independent investigator. Every numerical result was to be reported with a level of precision that matched its accuracy. Every search of the literature was to be complete and comprehensive, so that the investigator could demonstrate knowledge of all previous and relevant work and prove the new work's originality. The principle of Occam's Razor – a willingness to adopt the simplest of several competing explanations – was universally accepted, as was the notion that all conclusions could be subject to empirical test and possible rejection. The goal of science was complete explanation, or in statistical terms an $R^2$ of 1. When sample data were analyzed, all numerical results were to be subject to tests of statistical significance, to prove that they were not likely to be simply artifacts of the particular sample chosen, but properties of the population from which the sample was presumed to be drawn. All terms were to be rigorously defined, and vague terms were to be replaced by ones that met the standard of objectivity – rigorous and shared definition, such that two investigators would always agree on the outcome when the definition was applied.

These standards are of course collectively unattainable in all circumstances. They may be more attainable in some disciplines than others, and certainly it is possible to imagine a physicist having no difficulty adhering to them, and being fiercely critical of any study that appeared to relax them. But researchers in the general domain of this book clearly encounter situations in which one or more of them is distinctly problematic. This is not to say that one should therefore reject them outright, and follow the lead of those who have looked for alternatives to scientific principles – rather, they constitute goals to which research should attempt always to aspire, while admitting that it may sometimes fall short. This section explores three of these issues in some detail, and then argues for a renewed approach to scientific methodology that better reflects the real conditions under which spatial analysts currently work.

### 5.1 Collaboration, replicability, and the black box

Before the widespread adoption of computing, it was customary for instructors in statistics courses to insist that each student be able to carry out a test by hand, before using any computational aids. Only then, it was argued, would the student fully understand the process involved, and be able to replicate it later. In this simple world it was possible to assume that every researcher knew every detail of every analysis, and that the published version of the research would include sufficient detail to allow others to repeat the experiment and replicate the results.

This principle has come under fire in recent decades, for a number of reasons. Computational aids have advanced to the point where it is not possible for any one individual to comprehend fully all of the algorithms involved. The author recalls passing a threshold, some time around 1990, when it was no longer possible to believe that every aspect of a computational analysis could be replicated by hand, given enough time. Operating systems were perhaps the first such area of computing – by 1990 they had advanced to the point where it was no longer possible to believe they were the work of one person, or that any one individual fully understood every aspect of their operation. Today these failures are commonplace. The documentation of our more sophisticated software, including GIS, is often not sufficient to detail every aspect of an analysis, and it may be impossible to discover exactly how a given system computes a standard property, such as “slope”, from a given input (Burrough and McDonnell, 1998, detail some of the options, but many more can be hidden in the details of a given implementation). In effect the developers of software, many of them operating in for-profit commercial environments, have become authorities that must be trusted, and it is difficult to submit their products to rigorous and exhaustive test.

Moreover, researchers now find it increasingly effective to work in teams, each team member providing some specific expertise. Funding agencies often express a willingness to fund research that brings together teams from many disciplines, in the interests of greater collaboration and cross-fertilization of ideas. But such arrangements inevitably lead to situations in which no one individual knows everything about an analysis, and members of the team have little alternative but to trust each other, just as researchers often have little alternative but to trust software.

### 5.2 Keeping the stakeholders happy

Tools such as GIS invite researchers to become involved in the processes of policy formulation and decision making. The very architecture of GIS, with its database of local details and its procedures representing general principles, invites engagement with the ultimate users of research, since it allows decision makers to investigate the effects of manipulating outcomes in local contexts, and gives them many useful tools for implementing the results of analysis. A new subdiscipline, public-participation GIS, has grown up to study these issues, and to improve the use of GIS and spatial analysis in public decision making.

Many of the arguments for the use of technology in support of decision making – for spatial decision support systems (Densham, 1991) – center on the benefits of these tools in settings that involve the potentially conflicting views of multiple stakeholders. Much has been written about spatial-analytic techniques that support multiple views, and address multiple criteria (Voogd, 1983; Eastman, 1999; Thill, 1999; Malczewski, 1999). GIS may allow stakeholders to express their own views as sets of weights to be given to relevant factors. Saaty's Analytic Hierarchy Process (Saaty, 1980) is a widely used technique for eliciting such weights from stakeholders, and for deriving consensus weights and measures of agreement. Stakeholders benefit from the visualization capabilities of these systems, which allow them to see the effects of decisions in readily understood ways. They gain the impression that decisions are made *scientifically*, with abundant use of mathematics and computation, and are led to believe that these approaches represent a more objective, more desirable approach to debate and conflict resolution.

It is all too easy in such circumstances to see stakeholder satisfaction as the primary goal of the exercise. If stakeholders leave the room believing that a rigorous, scientific process has been conducted then everyone can feel that a useful exercise has come to an acceptable conclusion. None of this guarantees, however, that the results presented to the stakeholders are in fact based on good science. It is easy, with a little thought, to manipulate the outcomes of such processes to achieve hidden objectives. For example, when stakeholders are presented with five alternatives and asked to choose one, it is easy to see how the outcome might be manipulated by presenting a set that includes the desired outcome, plus four obviously unacceptable "red herrings". Experience suggests that stakeholders will find no difficulty in assigning relative measures of "importance" to factors, irrespective of whether the factors are or are not commensurate, and whether or not any definition of "importance" has been advanced and agreed.

### 5.3 Accuracy, uncertainty, and cost

All measurements are subject to error, and science has developed sophisticated techniques for measuring instrument accuracy, and for determining how accuracy impacts the results of analysis. The basic principles of error analysis have been adapted to the specific needs of geographic data by Heuvelink (1998) and others, and statistical models have been developed for most of the standard geographic data types.

Uncertainty is often defined as the degree to which data leaves the user uncertain about the true nature of the real world. As such it presents a greater problem, because it derives not from errors in measurement, but from vagueness in definitions, lack of detail, and numerous other sources. When definitions are vague, there can be no objective definition of truth, but only the less satisfactory concept of consensus. A scientist steeped in traditional methodology would react by rejecting vague terms entirely, replacing them with terms that have rigorous definition, and are therefore capable of supporting replicability. Subjective terms such as "warm", "cold", "near", and "far" would be replaced by well-defined scales of temperature measurement and distance.

Nevertheless, GIS and to a lesser extent spatial analysis clearly exist at the interface between the rigorous, scientific world of well-defined terms and replicable experiments, and the vague, intuitive world of human discourse. Many users of GIS appear happy to work with vaguely defined classes of vegetation or land use, and there has been much interest in building user interfaces to GIS that come closer to emulating human ways of reasoning and discovering. *Naïve geography* has been defined as a field that studies the simplifications humans often impose on the world around them, and writers have speculated about the potential for systems that also simplify – that "think more like humans do".

In the past decade or so there has been much interest in the application of fuzzy sets, rough sets, and related ideas in spatial analysis. There seems to be some degree of intuitive appeal in the idea of assigning degrees of membership to a class, even when the class is not itself well defined. Methods have been devised for eliciting fuzzy membership values from professionals, from remotely sensed data, and from other sources, and for displaying these values in the form of maps. All of these methods stretch the norms of science, by arguing that it is possible to observe and measure useful properties despite a lack of agreement on the definitions of those properties. As such, they demand a re-examination of the basic tenets of scientific method.

Finally, spatial analysts find themselves today in a world overflowing with data. Satellite images, digital topographic maps, and a host of other sources provide an unprecedented opportunity for new and interesting research. Massive investments have been made over the past decade in data warehouses, spatial data centers, and geo-portals, with a view to facilitating the discovery and sharing of spatial data. Metadata standards have been devised that support search, by allowing researchers to hunt through catalogs looking for data that might meet their needs.

Yet almost certainly data discovered in this way will fail to meet the exact needs of the researcher. The data set will be too generalized, not sufficiently current, too inaccurate, or inadequate in another of a myriad of possible ways. In these circumstances it is inevitable that research objectives become modified to fit the properties of the available data, if the alternative is an exercise in field data collection that may be impossibly expensive. But the prevailing methodology of science says nothing about such compromises, maintaining instead that data must be exactly fit for purpose, and providing no basis on which users can find compromises between cost on the one hand, and accuracy or fitness for use on the other.

## 5.4 Summary

The previous three sections have presented examples of the ways in which spatial analysts increasingly find the traditional principles of scientific methodology inadequate as a guide to practice. While much of science is concerned with the nomothetic goal of discovering general principles that apply everywhere in space and time, spatial analysis is increasingly concerned also with the variations that exist in such principles from place to place, and in the ways in which such principles are placed in local context to solve problems and make decisions. As Laudan (1996) has argued, there is no longer an effective methodological distinction between science and problem-solving, since the same principles apply to both. In summary, spatial analysts face an important challenge, to develop a new methodological understanding that is consistent both with the traditional tenets of the scientific method, and with the realities of current practice.

## 6. CONCLUSIONS

The four major sections of this chapter have argued that spatial analysis faces many challenges at this time, but it also faces unprecedented opportunity. More people than ever are aware of its potential, and the tools to implement it are more sophisticated and powerful than ever.

Discussions of the importance of spatial analysis often focus on one or two particularly compelling application domains, and it may well be that by making the case for spatial analysis in support of improved public health, for example, or better response to emergencies, it will be possible at the same time to promote the entire field. On the other hand, one might argue that identifying spatial analysis too clearly with one application domain tends to render the case for other applications more difficult. Essentially, it can be very difficult to promote a set of techniques that are applicable to almost *everything* – the case for spatial analysis is everywhere, and yet at the same time it is nowhere.

The argument for spatial literacy made in Section 4 seems especially relevant in this context. Many skill areas are important across a vast array of human activities, including skill in language, in mathematics, and in logic. Spatial analysis should not be a highly specialized area of technique that is only accessible to experts, but should be part of every citizen’s basic set of skills, and used every day in such basic activities as wayfinding and activity planning.

How the field responds to these challenges remains to be seen, of course. Undoubtedly new and better techniques will be discovered and published in the next few years, new code will be written, and new application areas will be described. But the challenges described in this chapter seem to go beyond such business-as-usual, and to require discussion across the entire community. Such community-wide debate has occurred very rarely in the past, yet is more feasible than ever with today’s communications technologies.

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