Prospects for a Space–Time GIS

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Space and time frame all aspects of the discipline of geography. Integration is normally interpreted by geographers as a straddling of the environmental–social divide, but a more profound interpretation stresses the issues involved in coupling environmental and social processes: a science of integration rather than an integration of sciences. Seven examples of distinct data types and scientific questions are examined, leading to the conclusion that a space–time geographic information system is unlikely to emerge in the near future. Instead, attention should focus on the systematic study of the issues involved in integration through the formal environment of a computational system. *Key Words: geography, interoperability, social/environmental integration, space–time GIS.*

空间与时间框架了地理学领域的所有面向。地理学者一般将整合诠释为跨越环境与社会之间的分歧, 但更为深刻的诠释则强调环境与社会结合过程中的议题: 一门整合的科学, 而非科学间的整合。本文将检视七个不同的数据类型及科学问题案例, 并引导至下述结论: 时空地理信息系统不太可能在不久的将来出现。反之, 我们则需聚焦关注对于藉由计算系统正式环境进行整合所牵涉的议题之系统性研究。 *关键词: 地理, 互通性, 社会/环境整合, 时空地理信息系统。*

Espacio y tiempo son dos conceptos que enmarcan todos los aspectos de la disciplina geográfica. Normalmente la integración la interpretan los geógrafos como una cobijadura de la divisoria socio–ambiental, pero una interpretación más profunda enfatiza los temas involucrados en el acople de los procesos ambientales y sociales: más una ciencia de la integración que una integración de ciencias. Se examinan en este artículo siete ejemplos de distintos tipos de datos y cuestiones científicas, a partir de lo cual se llega a la conclusión de que la aparición de un sistema de información geográfica del espacio-tiempo en el futuro cercano es dudosa. Mientras tanto, la atención debería concentrarse en el estudio sistemático de los asuntos involucrados en la integración a través del ambiente formal de un sistema computacional. *Palabras clave: geografía, interoperabilidad, integración socio-ambiental, SIG del espacio-tiempo.*

Geography[1] is a most Newtonian discipline, rigidly framed in space and time and focused on scales that are far too coarse to experience quantum effects and far to fine for relativistic effects. Everything of relevance to geography occurs somewhere, at some time, within this rigid frame. Since the 1980s, the majority of spatial references have used the WGS84 standard (the World Geodetic System of 1984), and since the late nineteenth century, Greenwich has provided the reference standard for time. Complications still exist, of course, in the legacy of other regional geodetic datums and other calendars, in the corrections that are periodically made to WGS84 because of improvements in geodetic measurements and in adjustments caused by tectonic movements. These are a small price to pay, however, for the essential simplicity of geography's reference frame.

Geography also stakes a claim to the title of "integrating discipline" or an "integrated science," because of its concern with both social and environmental phenomena and processes. Students of geography learn something of both the human and physical worlds, in contrast to the reductionism that dominates many other disciplines. But knowledge of both worlds seems a weak argument, especially when the expertise of a single geographer is compared to that of a team that includes specialists in each world; a geographer in this context is too easily dismissed as a Jack or Jill of both worlds but a master or mistress of neither.

A stronger argument relies on a more subtle and profound meaning of integrating discipline. Science has always been motivated by the desire to abstract knowledge from space and time, to provide general principles and laws that are true everywhere and at all times. Economics and ecology, for example, have both been enormously successful at abstracting such knowledge, in the form of statements or equations that govern their respective phenomena and processes. Prediction of the precise outcomes of such processes requires context, in the form of initial and local conditions, and is generally treated as of less import to pure science, although of great import to applied science, local policy, and

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decision making. Similarly, the observation of local conditions is also regarded as low-grade scientific activity and described somewhat pejoratively as descriptive or journalistic.

How, then, is the integration of economics and ecology to be valued? In what sense is their integration more than the sum of their parts, more than a serial recitation of their respective principles and laws? To integrate knowledge of economics with knowledge of ecology is meaningless without the context provided by space and time, and the interactions that occur between economic and ecological phenomena at a place and at a time, in a coupled natural–human system. Integration requires the ability to represent the variation of context, in the form of structured geographic databases; to represent processes in the algorithms of software; to couple these representations using identical discretizations of space and time; and to analyze the impacts of uncertainties in the representations. None of these forms of generic expertise and knowledge are traditionally recognized as elements of either economics or ecology, but they are all fundamental to geography and GIScience. In short, they represent what one might term the *science of integration*, as distinct from an *integrated science*.

Although this argument is posed here in the context of integrating the social and environmental sciences, it can also be applied to the integration of scientific knowledge across the disciplines of the environmental sciences or the social sciences. It is, for example, the knowledge that would be needed to integrate criminology and economics, or ecology and meteorology. It has been explored in depth in the social sciences through the work of the Center for Spatially Integrated Social Science, which was founded on the principle that space is essential to any conversation between social sciences (Goodchild and Janelle 2004). More broadly, it is the basis on which the University of California, Santa Barbara, established a Center for Spatial Studies in 2007 to explore the degree to which spatial thinking could help to break down the traditional stovepipes of a research university, by an emphasis on spatial perspectives that is not limited to geographic space but applies also to the spaces of the human brain, the cosmos, or nanoscience.

One more introductory and related point needs to be made. By focusing on space and time, a discipline that offers to provide the means to integrate knowledge across the sciences must of necessity discuss both the general and the specific—both the general laws and principles that science has abstracted from space and time and also the specific conditions at locations and times that provide the essential context to integration. In this light, the duality of a general and a specific geography, which dates back at least as far as Varenius (Warntz 1989) and had exceptional prominence in the 1950s and 1960s during the debates over idiographic and nomothetic visions of the discipline (Bunge 1966), is seen as both inescapable and unresolvable.

Geographic information systems (GIS) arose in the 1960s out of several disparate needs (Foresman 1998): to be able to make accurate, fast, and automated measurements from maps; to be able to use the power of computers to edit maps; to be able to incorporate numbers of dimensions into planning decisions; and to be able to handle large quantities of disparate geographic data in transportation planning. By the late 1970s, these needs had coalesced into a single set of tools for performing a wide range of operations on geographic information, and by the late 1990s they had evolved into the enormously powerful GIS of today. Although today's GIS supports many different data models and formats, it offers distinct advantages in combining all of them in a single software environment. For example, raster-based remote sensing data can be combined with vector-based administrative boundaries to answer cross-disciplinary questions concerning the distribution of habitat in populous counties.

It has nevertheless proven very difficult to move beyond the metaphor of the map as the conceptual framework for GIS. Today a GIS is still often presented as a computerized container of maps, performing operations such as overlay that can be readily understood in physical terms, rather than as a container of large collections of geographic facts that might or might not have been organized into maps. One casualty of the persistent map metaphor has been time, as maps have always favored the relatively static features of the Earth's surface, in the interests of ensuring the longest possible validity (Goodchild, Fu, and Rich 2007). Only recently have some of the more powerful time-dependent aspects of mapmaking begun to attract attention, in products such as the maps one can now readily obtain of local, real-time traffic conditions.

It is tempting to believe that the full incorporation of time into GIS is just over the horizon. Such a GIS would provide the ideal platform for the disciplinary integration discussed in the preceding paragraphs. It could address some of the long-standing critiques of GIS, including the arguments of Taylor (1990) and others that GIS is more concerned with geographic fact than with geographic knowledge, and it would provide a formal substantiation of the argument that geography is the integrating discipline. With this goal in mind, the next section addresses the question of whether such an extended GIS is both feasible and likely to emerge—whether it is, indeed, just around the corner.

Functions of a Space–Time GIS

GIS emerged in the 1970s from the coalescence of many interests that would not at first sight have been perceived as having much in common, apart from a focus on maps. Nevertheless, by the late 1970s it had become apparent that many different forms of map data could be handled in a single, unified structure and subjected to a set of generically defined operations. Comparisons were drawn between GIS and word processing packages such as Microsoft Word or WordPerfect, which were offering a range of operations on text, or the statistical packages (Goodchild 1988), which by the 1980s had begun to offer a full range of statistical techniques for the analysis of numerical data. GIS architectures have progressed far beyond the monolithic systems of the 1980s into the networks of distributed services represented by cyberGIS (Wang 2010) and the very limited services provided by in-vehicle navigation devices; nevertheless, the standards and data models of GIS continue to provide a single, unified platform and framework.

It is tempting, therefore, to compare the present state of space–time GIS (STGIS) with the state of GIS in the late 1960s and early 1970s, as a set of activities waiting for a unified framework to emerge from the efforts of the research community and software developers. In the following sections I investigate the current situation in detail, looking for the kinds of commonalities that led to the coalescence of GIS. Is there, indeed, room for a generic STGIS that unifies the functions needed to capture, store, analyze, visualize, model, and archive space–time data in much the same way that GIS has addressed the needs of spatial data? Will STGIS play a role in the discipline of geography in coming decades that GIS has played and continues to play? The following seven sections discuss seven distinct forms of space–time data and the scientific questions that arise in each case, although the greatest attention is paid to the first few. The list is not intended to be complete but rather to sample the range of possibilities to answer the central questions of this article.

Tracking

One of the more prominent new data types of the past decade results from the tracking of objects, using the Global Positioning System (GPS), radio-frequency identification (RFID), surveillance cameras, and other techniques. Vast amounts of tracking data are being collected on the movements of humans, vehicles, animals, and aircraft. In the case of humans, tracking is often without the full awareness of the person carrying the tracking device or hidden in the fine print of license agreements (see, e.g., recent news coverage of iPhone tracks being captured by Apple). Tracking creates a series of point observations that might be spaced by as little as a few seconds. In other cases, observation intervals are determined by the behavior of the object; in the case of whales, GPS observations can only be made and transmitted when the animal surfaces. Tracks can also be reconstructed from other kinds of events, such as the photographs that tourists upload to Flickr with times and georeferences or from the georeferenced tweets made by prolific tweeters.

Tracking allows geographers to ask a suite of new and interesting questions. Research on the detailed space–time behavior patterns of people and animals, long constrained by lack of data, has been greatly stimulated. Tracks of schoolchildren can be analyzed to infer metabolic rates in research on childhood obesity. Cell phones equipped with simple environmental sensors can be used to conduct detailed analysis of space–time air pollution. More broadly, we can anticipate significant new advances within the conceptual framework of time geography originally proposed by Hägerstrand (1970). Inferences about activities can be made by analyzing the speeds, directions, and convergences of tracks, and a series of recent papers have addressed the question of how to measure track similarity (Dodge, Weibel, and Forootan 2009).

Yet little progress has been made to date on creating generic tools for the analysis of tracks. ESRI's Tracking Analyst (ArcGIS, ESRI, Redlands, CA) allows limited forms of analysis on tracks, and Chen et al. (2011) have developed an important extension to ESRI's ArcScene software (ArcScene, ESRI, Redlands, CA) . But neither of these approaches treats tracking data within a larger, comprehensive framework that includes other forms of space–time data and might form the foundation of an STGIS. At this time, the evidence suggests that the analysis of tracking data will remain a largely isolated and specialized extension of existing GIS.

Temporal Sequences of Snapshots

A very different form of space–time data is found in the time series of remotely sensed images that have long provided useful inputs to research in geography.

Important techniques have been developed to detect change, to distinguish between real change and statistical noise (Pontius and Li 2010), and to interpolate between images to estimate the state of the landscape at times when it was not observed. Geographers and others have also devoted significant research effort to overcoming the inconsistencies that inevitably affect long time series, including changes of sensors and spatial resolution.

Snapshots fall within the SNAP (for snapshot) ontology of Grenon and Smith (2004). Although GIS and image processing packages include techniques specifically designed for their analysis, they are most often structured as unrelated images, and tools to organize them into sequences might or might not be implemented. Longitudinal compression techniques, analogous to the compression standards widely employed for video, are also rarely implemented. In PCRaster (Karssenberg et al. 2009), for example, a package developed in The Netherlands for the simulation of dynamic geographic processes, each snapshot is treated as a separate iteration, and input, output, and archived as such. Thus, the data models used to represent snapshots bear no relation to those developed for tracking data: Snapshots are conceptualized as sequences of cross-sectional continuous fields, whereas tracks are conceptualized as movements of discrete objects in space and time.

Temporal Sequences of Polygon Coverages

A third type of space–time data occurs in social science, when a set of zones that partition the plane, such as census tracts or counties, are used to report statistics on demographics, housing, or economics. I refer to these as *polygon coverages* because they are represented in GIS as collections of nonoverlapping polygons. Efforts are often made to ensure the persistence of boundaries through time, but where this is not possible, various techniques of reaggregation and areal interpolation have been used (see, e.g., the work of the National Historic GIS at http://www.nhgis.org).

Data such as these are commonly used to track evolving economies through time, to research residential segregation, to examine relationships between socioeconomic characteristics at the ecological level, and to study patterns of crime and health. The field of spatial econometrics studies such processes through models that incorporate explicit spatial effects, and a great variety of techniques of spatial analysis and modeling have been developed to take advantage of this data type (Fischer and Getis 2009). Although support is limited in GIS, Rey and Janikas (2010) have assembled a very impressive package of techniques known as STARS (space–time analysis of regional systems) for analysis of this data type, which is most easily structured as sequences of time-specific attributes for a single set of polygons. Again, this approach bears little relationship to the techniques used to model tracks or temporal sequences of snapshots.

Cellular Automata

Cellular automata derive from the work of Conway (Gardner 1970), modeling space–time processes on a fixed raster. Each cell of the raster is assigned a state, and the process is modeled as a set of state transitions through time, governed by a set of rules that are chosen to replicate some real environmental or social process. Cellular automata have been applied successfully in many areas of geography, including the modeling of the land-use transitions that occur during urban growth (Clarke, Hoppen, and Gaydos 1997). The PCRaster package described previously is a powerful environment for implementing cellular automata. In Conway's original work, the most compelling interest lay in the emergence of interesting patterns that would not have been predicted from an intuitive understanding of the rules. In geography, however, it is never clear whether such emergent patterns are real or the result of artifacts and uncertainties in the representation of the data or the transition rules.

Agent-Based Models

Agent-based models (ABMs) attempt to simulate real geographic processes through the actions and decisions of discrete agents. Each agent is typically represented as a discrete object and acts by moving and changing state according to specified rules of behavior. Conceptually ABMs are very similar to cellular automata but differ in the data modeling: Cellular automata always use rasters, whereas the movements of objects in ABMs are modeled as tracks. There is little evidence of any effort to create a unified modeling environment capable of handling both approaches or of including other space–time data types.

Events and Transactions

Events and transactions represent one of the most primitive of space–time data types: Each record represents a single event or transaction, together with its location in space–time and any relevant attributes. This is a domain familiar to the historian, in which events are linked spatially and hierarchically. For example, an election could be modeled as an aggregation of meetings and other events and different locations and times, and the campaign of an army might be modeled as a series of linked battles and skirmishes. In a similar fashion, monetary transactions might be linked by the individuals involved or by the locations in which they occur, in the kind of application represented by credit card use.

Multidimensional Data

This final example concerns environmental data that have been intensively sampled through time at a set of fixed points. Examples include weather data that are reported from fixed weather stations and water-level measurements in wells. Such data are technically geographic because every observation is georeferenced, but spatial patterns might take second place to temporal ones because of the comparatively intense temporal sampling. A common form of analysis is spatial interpolation, which is used to estimate values at locations away from the measurement sites and to create continuous fields in space or space–time. This data type is much simpler than many other forms of space–time data, being readily conceptualized as a hypercube, and is often distributed and shared using the netCDF (network common data form) standard.

Conclusion

I asked earlier whether the current situation with respect to space–time data was comparable with the situation in the late 1960s and early 1970s when a number of apparently unconnected efforts to handle geographic information coalesced into a software environment known as GIS. Even though that coalescence did not mature until the early 1980s, there was clear evidence of commonality as early as 1970, in the form of early meetings on spatial data handling organized by Roger Tomlinson through the International Geographical Union. The sessions on space–time integration organized at the annual meetings of the Association of American Geographers in 2011 provided ample demonstration of the importance of a space–time perspective but did little to advance the notion of a modeling environment that might qualify as an STGIS. Instead, the seven examples explored in this article provide ample demonstration that any coalescence is going to be very difficult and unlikely to offer the kinds of scale economies that have always motivated GIS. It is hard to identify questions that would require simultaneous analysis of tracking and cellular automata, for example; yet in the 1970s it was comparatively easy to identify questions that required the combination of raster and vector data or data from maps and data from remote sensing. In short, from today's perspective it is difficult to make a case for the coalescence of all or a subset of the seven examples.

Rather, it seems clear that the most useful role that geography and GIScience can play is in exploring a science of integration. There is clearly great interest in adding social scientists to the multidisciplinary teams exploring major questions in the environmental sciences; similarly, environmental scientists have much to add to research on human–environment interactions. But if this interest is to be translated into real, tangible results and useful advice to decision makers, it is clear that it will have to be formalized and implemented in the kinds of structured, replicable environments that computational systems can provide. One of the strongest arguments for the real-world application of GIS, or of any decision-support system, has been its ability to capture the process by which decisions were made, document it in replicable form, and present it during public meetings or litigation. Computational systems such as GIS impose a rigorous framework of data models and replicable processing, allowing data and results to be shared and discussed rigorously and objectively. They encourage shared terminology, as evidenced by recent work to develop geographic ontologies (see, e.g., http://www.spatial.redlands.edu/sds). In this way, computational systems can provide an essential infrastructure for effective multidisciplinary collaboration and integration.

In summary, the great disparity in different types of space–time data and questions illustrated earlier argue against the emergence of a single STGIS, in a comparable fashion to the emergence of the concept of GIS in the 1970s and 1980s. Instead, a number of distinct forms of STGIS are likely to evolve, based on distinct data types and suites of scientific questions. In this article I have explored seven of these. Others might well emerge, and there could be instances where two or more of the seven coalesce. For the scientific community, however, a focus on the underlying issues of space–time integration, modeled on the GIScience that emerged in the 1990s, could lead to significant advances and the creation of new knowledge. Many difficult and challenging issues will have to be explored if this vision of a science of integration is to materialize. They include many of the familiar questions of GIScience: how to visualize space–time data, how to address uncertainty, or how to analyze the effects of scale. Adding the temporal dimension, and operating in a multidisciplinary context that includes both social and environmental phenomena, makes the problem even more complex and challenging.

Note

1. In what follows, geography is understood to be a science. There are, of course, other approaches to the study of geography, but a focus on them is outside the scope of this article.

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