x. REPRESENTATION AND COMPUTATION OF GEOGRAPHIC DYNAMICS

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Abstract

If the geographic domain is defined as the surface and near-surface of the Earth, then geographic dynamics describes all time-dependent aspects of that domain, including the results of processes that transform and modify it. This is a vast field, encompassing both social and physical phenomena. GIScience traditionally focuses on the scientific issues that lie behind GIS. In the context of geographic dynamics, it seems appropriate that GIScience focus similarly on the generic: the tools, data models, software, and other resources that facilitate analysis and modeling of dynamic phenomena. Fields and objects provide a useful framework for further discussion, since processes can be identified as field-based, object-based, or based on both conceptualizations. We review the currently available resources, and identify some significant gaps. The example of flow-like phenomena provides a case study of the development of generic data-modeling tools. Five gaps are discussed in detail, as the basis for a research agenda on geographic dynamics for GIScience.

x.1 Introduction: The Domain of Geographic Dynamics

In the parlance of computer-aided software engineering (CASE), one designs solutions to problems in a domain by identifying a series of representative *use cases*. Success depends on choosing a sufficient number of use cases to sample the domain adequately, characterizing the variety of likely applications of the system. By this logic, the design of systems to represent and compute geographic dynamics requires an understanding first of the domain of geographic dynamics, and second of the range of uses to which such representations and computations will be put. In short, to discuss representation and computation of geographic dynamics we must first understand the full range of geographic dynamics, and then ask why such representations and computations are useful.

The adjective *geographic* refers primarily to the surface and near-surface of the Earth. For many purposes the two-dimensional surface is sufficient, but atmospheric scientists, geologists, and mining engineers are also interested in areas above and below the surface, and in full three-dimensional knowledge about these domains. Thus the geographic domain can be defined as the roughly 500 million sq km of the surface, together with the first 20 km or so above the surface, and the first 20 km or so below it. Spatial resolution within this domain is a little harder to quantify, but there is little significant interest in resolutions coarser than 10 km, or in resolutions finer than 10 cm.

Dynamics refers to change through time, and the characterization, understanding, and prediction of such change. Change in the geographic world can be as a result of naturally occurring processes, such as erosion, or human-induced change, such as global warming. Dynamic phenomena extend from the daily journeys to work made by commuters, to the changes of land cover induced by wildfire or severe storms, to tides and currents, to changes in land use as a result of urban development. In the traditions of cartography and geographic information science (GIScience) such phenomena have been difficult and expensive to record and store on maps or in databases, and geographic information systems (GIS) have often been criticized for not accommodating knowledge about the dynamic aspects of the Earth's surface. Topographic mapping practice tends to emphasize the relatively static aspects of the surface, such as terrain, hydrography, and built form, and such practice has been inherited by GIS, which were developed originally in large part as systems for storing the contents of maps (Goodchild 1988).

Defined in this way, the domain of geographic dynamics is clearly vast, since it spans the concerns of a large number of disciplines that includes geography but also virtually any discipline concerned with change in geographic space: geology, atmospheric science, ecology, economics, criminology, and many more. A wide range of tools have been developed in recent years to address this domain, including tools for visualization, simulation of the actions of agents, the operation of cellular automata, the solution of partial differential equations, and much more. PCRaster (http://pcraster.geo.uu.nl; Burrough, Karssenberg, and van Deursen 2005) is perhaps the most prominent example of a GIS designed specifically for dynamics, and though as its name suggests its functions are primarily in the raster domain, nevertheless a stunning array of examples have been explored, and it is clear that remarkably convincing simulations of processes operating in the geographic domain can be simulated with very simple rules. Examples range from the growth of volcanoes and the erosion of fault-block topography to seed dispersal and the movement of groundwater.

Also in the raster domain, researchers have used simple rules to simulate the changes of state that occur in urban growth and other changes of land use. These models are best seen as examples of cellular automata, made popular by John Conway. Clarke's SLEUTH model is of this type (Clarke, Hoppen, and Gaydos 1997), and has been applied to the modeling of urban growth in several areas of the U.S., and similar models have been described (see, for example, White, Straatman, and Engelen 2004). In atmospheric science modeling has reached a high level of sophistication. At the global scale, a number of global climate models (GCMs) have been built to provide numerical solutions to the partial differential equations governing the atmosphere, and similar models have been constructed at the mesoscale to address local atmospheric phenomena. The modeling of tidal movements and ocean currents has also reached a high level of sophistication.

Agent-based models attempt to simulate the movements and actions of individual, autonomous agents, and have had success in the study of the behavior of pedestrians in cities (Batty 2005), tigers in India (Ahearn and Smith 2005), and vehicles on congested highways. The use of GPS (the Global Positioning System) to track samples of individuals in cities has led to useful new knowledge about travel behavior (Kwan and Lee 2004). Finally, much progress has been made in the modeling of severe storms and their impacts (Yuan 1999, 2001).

x.2 The Role of GIScience

What role should GIScience play within this vast and complex domain? Modeling of dynamic geographic phenomena is well established in many disciplines ranging from atmospheric science to hydrology and transportation. Just as GIS attempts to provide a generic set of tools to support the analysis and manipulation of geographic information, we propose that GIScience should similarly address the generic spatial components of dynamics, by devising answers to such questions as the following. What are the common aspects of modeling that span the entire domain of geographic dynamics? What generic tools can be designed to support the domain? What languages might provide generic support, allowing models in a wide range of application areas to be defined in a common, interoperable syntax? Is it possible to conceive of a generic data model that specializes the concepts of GIS to the needs of geographic dynamics, and in turn can be specialized to the needs of specific application domains? What general properties are exhibited by dynamic geographic phenomena that might constitute laws of geographic dynamics comparable to Tobler's First Law (Tobler 1970; Sui 2004)?

This is not a simple charge, because it implies knowledge of the entire domain, and the ability to generalize from all of its aspects. If it has taken GIS 40 years to advance from its primitive beginnings, with prototypes that addressed very specialized applications, to the generic tools of today, then the task of addressing geographic dynamics is clearly at least as forbidding. But this pursuit appears to be the only rational way to approach the question of the appropriate role for GIScience.

The distinction that is often drawn between form and process (Goodchild 2004) seems to be a useful way to begin to structure this charge, and to create a conceptual framework within which it can be addressed. Form is defined as how the world *looks*, and clearly this definition resonates with the traditions of GIS, with the reliance on the map as the primary source of GIS data, and with the use of imagery representing instantaneous snapshots of the Earth's surface. Spatial analysis has typically emphasized the power of such *cross-sectional* data to reveal useful insights into patterns of phenomena on the Earth's surface. Tobler's First Law stands as a powerful generalization about geographic form, and provides the basis for spatial interpolation and the fields of spatial statistics and geostatistics.

Nevertheless, the concept of how the world looks can be readily generalized to the spatiotemporal case. Three-dimensional visualizations of tracks, for example, are snapshots that focus on form, albeit over finite ranges of both space and time, and provide potential insights into individual behavior. Thus a change of emphasis in GIScience from space to space-time does not necessarily imply a simultaneous change of emphasis from form to process, or from how the world looks to how the world *works*. The distinction between form and process is not so much a distinction between space and space-time as one between data and rules; between the data that describe the details of how the world looks, and the rules, equations, and algorithms that describe how it works, and how it is transformed from a state at time t_i to time t_{i+1}.

Such rules, equations, and algorithms are most useful if they apply everywhere in space and time. The Second Law of Thermodynamics or the Periodic Table of the Elements would be of little value if they applied only in Nebraska, for example, or only on Tuesdays. Such knowledge is termed *nomothetic*, to distinguish it from detailed knowledge about the unique properties of times and places, that is, *idiographic* knowledge. The scientific community is in no doubt about the comparative merit of nomothetic knowledge, and terms associated with idiographic knowledge, such as *descriptive* or *anecdotal*, can be distinctly pejorative. From a GIS perspective, the distinction between nomothetic and idiographic aligns closely with the distinction between the software -- the methods, scripts, procedures, and algorithms -- and the database of local detail to which the software is applied, and which it transforms.

In summary, then, the role of GIScience in this context of geographic dynamics is to find general structures that support the domain. These may take the form of algorithms, simulation models, data models, languages, standards, knowledge about the modeling and propagation of uncertainty, etc. By looking for generic solutions, GIScience pursues structures that are sharable, formal and unambiguous, reusable, and thus efficient.

x.3 Fields and Objects

The distinction between continuous-field and discrete-object conceptualizations appears to lie at the most fundamental level of GIScience. Briefly, continuous fields map every location in space-time to a variable, $z = f(\mathbf{x})$ where z denotes a property and may be nominal-, ordinal-, interval-, or ratio-scaled, and may denote a scalar or a vector. Examples include elevation and soil class as scalar functions of the two horizontal dimensions, and wind speed and direction as a vector function of the three spatial variables and time. Discrete objects, on the other hand, represent a conceptualization of the geographic world as an empty space littered with points, lines, areas, or volumes, each having a set of homogeneous properties. Discrete objects may be persistent through time, and may change shape and move.

The field/object distinction provides a convenient framework for the discussion of geographic dynamics. Some processes are conceptualized entirely within the field domain. They include those described by partial differential equations (PDEs): the behavior of viscous fluids (the Navier-Stokes equation) and of groundwater (the Darcy flow equation), and electromagnetism (the Maxwell equations). PDEs are normally solved in space-time using one of two methods: finite differences (FD) and finite elements (FE). FD methods approximate the derivatives

$$\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, \frac{\partial^2 z}{\partial x^2}, \frac{\partial^2 z}{\partial x \partial y}, \text{and} \frac{\partial^2 z}{\partial y^2}$$

using differences in a simple raster, and are therefore readily supported by raster functions in GIS. Derivatives in time are approximated by taking differences between consecutive rasters. The routine GIS function of slope calculation from a DEM is a simple example of numerical approximation, giving an estimate of the derivative of the field with respect to the horizontal dimensions. FE methods use an irregular mesh, and while this bears some resemblance to the TIN (triangulated irregular network) of GIS, FE meshes commonly utilize both triangles and quadrilaterals, represent variation within elements using curvilinear functions, and require continuity of value, gradient, and curvature across element edges (Carey 1995). By contrast, TINs conventionally require only continuity of value and assume linear variation within elements. Thus the TIN model would be problematic for the solution of PDEs because gradients are undefined across edges. Moreover, some global climate models are operationalized entirely in the spectral domain, requiring none of the spatial discretizations common in GIS.

Because of their similarity to raster methods, FD solutions of PDEs can be implemented readily in GIS, particularly in PCRaster, which uses a command language (van Deursen 1995) that can easily accommodate such applications. Software for the simulation of cellular automata can also be adapted fairly readily to FD solutions. Packages such as PCRaster and ESRI’s ModelBuilder (http://www.esri.com/software/arcgis/about/modelbuilder.html) will support the loops needed in any iterative algorithm. However, these packages adopt a very simple approach to data management, in which each time interval is maintained as a separate raster layer, and each time step requires the input and output of at least two complete layers. Much more sophisticated approaches to the storage of ordered stacks of rasters have been devised, notably in the interests of compressing video (http://www.mpeg.org), and could be implemented or adapted to improve the performance of iterative GIS algorithms.

The integration of FE methods with GIS has proceeded much more slowly, however, and to date FE meshes are not one of the representations of fields that are supported by the most popular products. Some efforts to integrate FE software with GIS have been reported, where the GIS is used primarily to prepare data, to visualize results, and to analyze results in geographic context. Lack of support for FE methods is one of the more obvious gaps in current GIS support of geographic dynamics.

While some processes are conceptualized entirely within the field domain, others are conceptualized as interactions between objects. Gravity provides one example, since the movements of celestial objects are modeled through the object-to-object forces defined by the inverse-square Law of Gravitational Attraction. Once the number of bodies exceeds two the mathematics rapidly becomes intractable, and the Many-Body Problem is notorious for its complexity.

In the geographic domain, object-based concepts of process can be found in the Spatial

Interaction Model (Fotheringham and O'Kelly 1989) and its applications to travel behavior, migration, and social interaction. Batty (2005) has modeled pedestrian flows during London's Notting Hill Carnival using simple rules of inter-object interaction, and similar methods have been used to model animal behavior. Software support is provided by several comprehensive packages for modeling autonomous agents, including SWARM (http://www.swarm.org) and REPAST (http://repast.sourceforge.net), and the latter has been integrated with ESRI's ArcGIS in the Agent Analyst extension (http://www.institute.redlands.edu/agentanalyst/AgentAnalyst.html). ESRI's Tracking Analyst provides some basic capabilities for handling the space-time trajectories of objects, and recently Google Earth (http://earth.google.com) has announced an extension to handle moving objects, though its capabilities are focused on simple visualization.

In a recent paper Goodchild, Cova, and Yuan (2007) argue that the dynamic behavior of objects can be captured in three fundamental dimensions. The vertical dimension of Figure 1 represents object shape, and distinguishes between objects that retain shape through time and objects that change shape. For example, a vehicle generally behaves as a rigid body through time, whereas clouds tend to change shape rapidly. The dimension towards the viewer represents an object's internal structure, and distinguishes between objects that are homogeneous (as tradition in GIS demands) and objects that have internal variation that may also be changing in time. For example, severe storms have complex and evolving internal structures. Finally, the dimension away from the viewer represents movement, and distinguishes between objects that are fixed and those that move through time. The traditional GIS representation, with its static, homogeneous objects is represented by the lower left corner.

[Figure 1 about here]

Implementation of object-based processes is also aided by developments in object-oriented data modeling, and specifically by the widespread adoption of Unified Modeling Language (http://www.uml.org) as a CASE tool for database design. In this environment it is easy to implement representations of dynamic phenomena, including events, transactions, and flows (see the next section), that would never have been possible under the earlier map-based conceptualization of geographic reality. Smooth integration of UML-based designs, developed in graphics environments such as Microsoft's Visio, with GIS packages such as ESRI's ArcGIS has vastly improved our ability to represent dynamic phenomena in formal, readily sharable ways (Arctur and Zeiler 2004); this strategy is explored further in the next section, which focuses on the modeling of flows as an example. Other data modeling developments include CityGML (http://www.citygml.org), an extension of GML (Geography Markup Language), which is itself an extension of XML (eXtensible Markup Language), that integrates the representations of 3D structures into standard GIS data models, using IFC, the international exchange standard of the construction industry.

Finally, some concepts of process combine both objects and fields. A ball rolling downhill provides a simple example, in which the ball (a discrete object) responds to the gradient of a field (elevation). Other examples include aircraft tracks through a field of wind, which are typically optimized to minimize travel time and fuel consumption, a home buyer looking for a suitable neighborhood and responding to continuous variation in perceived suitability, and a fugitive searching a landscape for concealment sites. Some relevant methods are included in current GIS, such as the calculation of geodesics (de Smith, Goodchild, and Longley 2007), but by and large the support for such processes is currently weak.

x.4 An Example: Representation of Flows

This section focuses on flows, in order to provide an example of how object-oriented data modeling can offer general, formal solutions to problems of representation in geographic dynamics. As noted at the outset, any representation that claims to be generic must demonstrate its applicability over all of a defined domain. More specifically, the data model must provide a *slot* for the storage of all information relevant to a particular application or use case; and use cases must be chosen to sample all of the defined domain.

We defined three use cases as representative of the domain of geographic flows. The first was a summary table of migrations between U.S. states in the period 1995 to 2000, as reported by the U.S. Bureau of the Census (Figure 2). The second was the famous Minard map of Napoleon's 1812 Russian Campaign, showing the route of the army, major events of the campaign, and the steady diminution of the army's size from over 600,000 to little more than 10,000 (the map is celebrated by Tufte, 1983, as an example of very effective and economical visual display of information). The map is shown in Figure 3 as re-rendered using modern GIS mapping tools (ESRI's ArcGIS). The third use case was the hydrology of part of the Central Kentucky Karst (Figure 4), an area of mixed surface and underground flow, where all of the surface routes and some of the underground routes are known and mapped, but where other underground routes have been inferred by dye tracing.

[Figure 2 about here]

[Figure 3 about here]

[Figure 4 about here]

Taking these three use cases, we identified the classes of objects present in each case. For the migration data, these were the origin and destination objects, and the flows between them. We identified the relevant attributes of each class, and developed a UML diagram showing each class, relationships between the classes, the attributes of each class, and any methods associated with the class. For the Minard map, the various segments of the march formed one class, and the events along the route another. The map shows the size of the army as a continuously changing attribute of the route, requiring a functional representation as a UML method, an option that is not widely implemented in GIS network software.

One of the aspects common to both the karst map and the migration data is the presence of inferred routes, where flow follows an unknown track. In the migration case, for example, we have no knowledge of the actual tracks followed by migrants, and in the karst case the unexplored underground routes of water are similarly unknown. Cartographically, such inferred paths are often shown as dashed, and depicted as simple straight lines (Figures 2 and 4).

Figure 5 shows the final merged result, in which each class is defined generically and given attributes that are common across all use cases. When the model is applied to any of the three use cases, each class is specialized to meet the context, and additional context-specific attributes are added. Starting from the left, each flow on the map forms a class, with an associated ID. Flows may be associated either with network reaches, which are real tracks on the Earth’s surface and associated with polylines, or with implied links. Implied links are associated with input and output nodes, which are associated with polylines through connections represented by the incidence class.

[Figure 5 about here]

By giving flow phenomena this formal structure we ensure that systems can be made interoperable, and that terms can be shared between widely divergent applications. The data model has been integrated with ESRI's ArcGIS, and a collection of tools are available for help with populating the model, specializing it for applications, and building analysis scripts (http://dynamicgeography.ou.edu/flow/index.html).

Galton and Worboys (2005) also use flows in networks as an example of the representation of dynamic geographic phenomena, based on traffic in transportation networks as the use case. Their model also includes the notion of continuous change of attributes along links, which they term *seepage*. Their concept of dynamics extends to the construction of new links and the deletion of existing ones, but the need to deal with inferred links did not arise in their use case.

x.5 An Agenda for GIScience

Although geographic dynamics is a vast domain, the simple conceptual framework presented above does at least allow the identification of significant gaps in our current abilities, and the basis for a research and development agenda. In this section we discuss five topics that in our view constitute significant gaps, and review the current state of the art with respect to each of them.

x.5.1 Languages for object dynamics

From a GIS perspective, there is a conspicuous difference between the high level of development of languages for handling raster dynamics, and the comparable state of languages in the vector domain. As early as the late 1980s Dana Tomlin was developing Map Algebra, a simple synthesis of raster operations into four basic types (Tomlin 1990). PCRaster's scripting language, the subject of a monograph by van Deursen (1995), provides a much less verbose and more rigorously defined replacement, and a comprehensive underpinning for modeling field-based processes. It allows entire fields to be addressed through symbols, and defines a series of functional operators that cover most of the requirements of implementing cellular automata and FD approaches to PDEs. For example, the statement C = A + B directs the system to add each cell's value in raster A to the corresponding cell's value in raster B, to create a new discretized field C. As such it provides a vastly simpler alternative to programming in the traditional source languages.

Despite this progress, and the popularity of implementations of Map Algebra in many GIS packages, the equivalents for vector representations of fields and for object dynamics have as yet failed to emerge. Kemp (1997a,b) and Vckovski (1998) have argued that the user interface to a GIS could be vastly simpler if fields could be addressed symbolically, independently of their discretization and spatial resolution. For example, the statement C = A + B might be executed even though A was represented as a raster and B as a TIN, the system making the necessary decisions about interpolation methods and the best representation for C (perhaps using A's raster and the average value of B within each cell, on the grounds that the spatial resolution of the raster is explicitly defined whereas the TIN's is not). In this approach the task of polygon overlay, long celebrated as the most daunting of GIS operations, would never be invoked explicitly, but triggered automatically whenever an operation required the mixing of two different spatial discretizations.

The basis for such a language might lie in relational algebra, given the power of object-oriented approaches in representing object dynamics. Clues to a solution might also be found in languages of object dynamics such as STELLA, which lack the focus on space-time but have powerful tools for representing interactions.

x.5.2 Software objects for dynamics

Over the past decade or so developments in software engineering have radically transformed the nature of GIS software, largely replacing monolithic packages with collections of reusable components. One software developer can now market many different products aimed at specific niches, while knowing that key code objects need to be developed only once. Functions implemented as components in GIS software can now be integrated with components from other packages, under the control of scripting languages such as VBA (Visual Basic for Applications; see for example Ungerer and Goodchild 2002) or Python (http://www.python.org).

Such strategies represent a high level of understanding of the domain, because they require software developers to identify the fundamental granules of data manipulation. In GIS there is significant consensus on this issue, but in the domain of geographic dynamics consensus appears to be largely absent. As we have argued, the domain of geographic dynamics is vast, spanning many disciplines. Bennett (1997) has reported significant progress on this issue, but more broadly we still lack a clear consensus on the set of tasks that constitute computation of geographic dynamics, and the fundamental components into which those tasks can be decomposed. Instead, most efforts at modeling processes are implemented as stand-alone software in source languages such as C, with very little reuse of code. Similar comments can be made about the failure to date to achieve reusability in the coding of spatial decision-support systems.

x.5.3 A UML equivalent for fields

Despite the success of object-oriented data modeling, its fundamental assumption that the geographic world is populated by *things* that can be grouped into classes ultimately limits its application, and creates a distortion – a sense of square peg in round hole – when used to structure geographic information. Many geographic phenomena are continuous, and the task of breaking them into discrete things limits the questions that can be asked about them, and the applications that can be built on databases. For example, terrain is continuous, and breaking it into discrete triangles inevitably creates distortion. Similarly rivers and roads are continuous, and must be broken into pieces at nodes in order to fit the concepts of object orientation. Unfortunately, GIS software does not record the lineage of objects that are used to represent fields, and as a result is capable of irrational acts. For example, if terrain is represented by a collection of digitized isolines, it is possible to edit their positions so that they cross, even though this is impossible in reality. Similarly some systems allow polygons representing a variable such as *owner* to be moved around freely, violating the requirement of any field that each location in the plane map to exactly one value of the function.

We believe that a first step in correcting this deficiency would be through the definition of an equivalent of UML for fields. If the isolines of a terrain representation were identified in this way, then methods could be associated that would prevent intersection during editing. In Figure 6 we present one possibility, in which the class of an object-oriented design is replaced by the discretization of a field. For example, in a raster GIS with each layer exactly coincident in space, we would have a single discretization (the raster) with a series of variables, each corresponding to one of the layers and representing the fields that are discretized using this raster. The details of the discretization – spatial resolution, geo-registration, compression method, etc. – would be defined as a property of the discretization itself.

[Figure 6 about here]

In UML several types of relationships are recognized between classes: inheritance, association, aggregation, and composition. One type of relationship between boxes in this field-based schema might represent the techniques needed to change representation, and might be termed *transformation* relationships. They might include spatial interpolation, to transform between point samples and a TIN for example, or digitized isolines and a regular sampling grid, or the resampling or aggregation methods needed to change a raster's spatial resolution. In the equivalent of an inheritance relationship, we would expect each box to specialize one of the six types of discretization commonly found in GIS, by defining the exact details of the discretization's geometry. Some discretizations, such as the state boundaries of the U.S., would have a very large number of variables, while in other cases, such as a TIN representation of terrain, only one variable would likely be associated with the box. Some discretizations, such as the state boundaries, might apply to a temporal sequence of snapshots, while others, such as the isobars of a weather map, would necessarily change with every snapshot.

In the figure, which shows a simple example of this graphic way of representing fields, the seven boxes across the top represent seven types of spatial discretization (the normal six of GIS, plus the finite-element mesh). The names are shown in italic, following the normal UML convention denoting an abstract class. Two types of discretization are shown with associated methods: irregular polygons representing a field must not overlap and must exhaust the space (*planar enforcement*), while polylines representing the isolines of a field must not cross. Open arrows indicate inheritance, and in this case two specific rasters are shown, one a DEM with a 30m spacing between sample points, and one an image, each pixel of which carries the values of four bands and a classification. Two specific discretizations specialize the irregular polygon type, one the result of vectorizing the classified image, and one recording several variables collected for census-tract reporting zones. Other links between boxes represent methods of transformation between discretizations, and may be directional if the transformation is appropriate only in one direction.

x.5.4 Continuous versus one-time analysis

One of the corollaries of a largely static view of the world is that analysis can proceed at a leisurely pace, since the data will not change before it is completed. GIS has largely adopted what might be termed a *project-based* or *one-time* approach, in which data are collected, analysis is conducted, and results are presented and published over a fairly lengthy period of time. But as geographic dynamics become more and more central to GIScience, the fact that data change continuously in a dynamic world forces us to rethink this basic aspect of the paradigm. Applications such as wildfire management (http://activefiremaps.fs.fed.us), early warning of famine (http://www.fews.net), and response to emergencies all dictate a pace of analysis that matches or exceeds the pace of actual change. In many cases the need is for a continuous monitoring, in which analysis constantly responds to new data.

In this context it is interesting to note the paradigms represented by the leading GIS software products. Intergraph’s GeoMedia (http://www.intergraph.com) could be considered to have a pipe-like structure, with data at one end and the user’s screen at the other. Analysis is conceptualized in the form of filters that are interposed on the pipe, allowing the user to expose different views of the data, or to perform simple statistical manipulation. This architecture is clearly much more compatible with the notion of a dynamic database than the traditional one.

x.5.5 Sensor networks

Recently there has been much interest in the concept of sensor networks, or distributed collections of interconnected sensors that transmit measures of their environment, along with information about location, to central servers that interpret, compile, and redistribute data to users. The U.S. National Science Foundation has funded a sensor-network graduate program at the University of Maine and a Science and Technology Center at the University of California, Los Angeles, among other projects.

It is important to recognize that the sensors may range from inert, fixed objects to GPS-enabled devices carried by humans, to humans relying on the normal senses. In this sense the term *citizen science* is relevant, describing as it does the use of extensive networks of human observers to collect and compile useful data. The Christmas Bird Count (http://www.audubon.org/bird/cbc) is only one example of an increasing number of ways in which individuals empowered by mobile technologies become effective sensors of useful geographic information. Recently, a number of projects have built on the success of Wikipedia (http://www.wikipedia.org) by encouraging individuals to uplink geographic information about their local areas, particularly information that can be used to enrich the *gazetteer* or names layer. Other groups are developing cost-effective maps by driving streets in vehicles equipped with GPS. In each of these cases groups of individuals provide a cost-effective alternative to the traditional mapping agencies, and a way of addressing their problems over declining budgets and increasing demands.

Sensor networks and citizen science offer interesting ways of addressing the supply of data about geographic dynamics. But many questions arise: how can masses of potentially conflicting data be assembled into useful databases; how can quality be assured, and what kinds of institutional arrangements would be needed; and what strategies can overcome the scaling issues of massive networks?

x.6 Conclusions

The first section of this chapter addressed the question of the domain of geographic dynamics, and concluded that it included virtually all disciplines that deal with the surface and near-surface of the Earth, and virtually all mechanisms that modify and transform that domain. This is an enormous charge, requiring effective communication and collaboration between a highly distributed set of researchers and users. Its intersection with the discipline of geography is uneven, since it encompasses some areas where geographers have made substantial contributions, including hydrology and biogeography, and others, such as tidal dynamics, where it would be very hard to find a specialist geographer.

Within this domain, we argued that the focus of GIScience should be on the generic – on the tools, data models, software, standards, and other structures that can support the domain as a whole. This is a difficult task, requiring a comprehensive knowledge of the domain and an ability to generalize about its requirements. But such generic support can be enormously cost-effective, interoperable, and helpful in integrating a multidisciplinary enterprise.

To provide a conceptual framework, we invoked the concepts of continuous fields and discrete objects, arguing that all processes are defined either as interactions between fields, interactions between objects, or interactions between objects and fields. Within this framework it was possible to review existing tools and other forms of support, and to identify significant gaps where little or no generic support exists. We argued that the distinction between nomothetic and idiographic knowledge was also relevant, in that knowledge of form, the traditional focus of GIScience, belonged to the idiographic realm while knowledge of process was essentially nomothetic. We also argued that the structure of modern GIS, with its separation between the local detail of the database and the general procedures of the software, epitomized the idiographic/nomothetic distinction.

Finally, we identified five areas, or gaps, where current knowledge and technique falls far short of what is needed if GIScience is indeed to provide generic support for geographic dynamics. Some of these involve improvements to representation, some to computation, and some to the organizational frameworks in which such work is embedded. A focus by the GIScience community on these and other deficiencies in our current state of knowledge will do much to move our collective capabilities forward, and to strengthen the contribution of GIScience to the representation and computation of geographic dynamics.

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Figure Captions

1. A representation of three fundamental dimensions of discrete-object dynamics (Goodchild, Yuan, and Cova 2007; reproduced by permission of Taylor and Francis).

2. Cartographic depiction of the largest state-to-state migration flows in the period 1995-2000.

3. A re-rendering of the Minard map of Napoleon’s 1812 Moscow campaign.

4. The hydrology of a part of the Central Kentucky Karst. Red lines indicate inferred flows.

5. A generic data model for flow phenomena.

6. A possible graphic representation of continuous fields. Each box represents a distinct spatial discretization, with associated variables. Open arrows indicate inheritance or specialization relationships. Other connections indicate methods for transforming between discretizations (see text for further details).