Analytical Map Use

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ABSTRACT. *Two perspectives on cartography are drawn together by examining virtual map use in spatial-analytical systems: the "map as a presentation image" and the "map as a computational tool." Map use is characterized in terms of three levels of tasks and two types of information products commonly generated. Level-one tasks include distinguishing individual symbol differences, the most basic information on a map. Level-two tasks include identifying clusters of symbols. Individual symbols and clusters of symbols constitute surface-structure information on a map. Level three, the primary focus of this article, includes decision-making and content-knowledge-building activity for geographical problem solving. Such tasks emphasize the use of deep-structure information on maps. Deep-structure information, also called conceptual information, primarily consists of geographical relationships as part of spatial context and meaning. Both surface and deep structure compose an information structure. An information structure is important in providing a context for query-mode and product-mode information products primarily at level three. Spatial data models capable of storing and/or deriving information structures are discussed using a spatial-analysis perspective. More flexible data models are required to store and manipulate geographic data semantics if level-three tasks are to be addressed. Such data models can form the basis of social-science geographic information systems (GIS).*

KEYWORDS: *analytical cartography, map use, surface structure, deep structure, information structure, data model, social-science GIS.*

Emphasis in Cartography: Is it Really One or the Other?

Fundamental issues in cartography during the past several years have involved either a communication or an analytical perspective. Communication cartography emphasizes the "map as a communication device" (i.e., a map used as a presentation image) (Board 1967; Morrison 1978). Analytical cartography emphasizes the "map as an analytical device" (i.e., a map used as a computational tool) (Tobler 1976). Cartographic activities using these perspectives tend to emphasize either a map-construction (production) focus or map-use focus. Thus, cartographic activities can be described as an emphasis that combines focus and perspective (Table 1).

Since any one cartographic activity probably does not fit neatly into a single category, the characterization here is more of elucidation of emphasis than strict classification. Although a difference in emphasis has been stimulating academically, perhaps a concern with synthesis would be more useful than demarcating the boundary lines. A recent deconstruction of maps (Harley 1989) complaining of sterile technologies of computer cartography suggests such synthesis. A deconstructionist point of view emphasizes that culture and institutions influence the nature of information significantly. This influence is very important in understanding the development and use of spatial information (Chrisman 1987). Despite the demarcation of communication and analytical cartography in the past, this article attempts to draw the perspectives together by focusing on the rows rather than the columns in Table 1, particularly with respect to map use.

Different map types exist based on the nature of technologies employed in their creation; however, there are differences in what one can do with them. Moellering (1980, 1984) distinguished different types of maps according to whether they are directly viewable and whether they have a permanent, tangible reality. Moellering called maps that are directly viewable and have a permanent, tangible reality "real maps" (e.g., conventional sheet maps). A map that is directly viewable, but does not have a permanent, tangible reality is called a "virtual map, type I" (e.g., an image on a computer monitor). A map that is not directly viewable, but does have a permanent, tangible reality is called a "virtual map, type II" (e.g., a map stored on a laser disc). A map that is not directly viewable and does not have a permanent, tangible reality is called a "virtual map, type III" (e.g., a data base stored on magnetic disc). Moellering (1980) pointed out that one of the major advantages of virtual maps is the user's ability to support transfor-

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Table 1. Emphasis of cartographic activities.

	Perspective: Communication (map as image)	Analytical (map as computational tool)
Focus:		
Map construction:	visual symbol design	data structure design
Map use:	reading, measuring, visualizing	analytical modeling

mations between the map types, which brings about new strategies for real-time cartography.

The focus of this article is the use of virtual maps, types I and III, particularly type III. Virtual map, type III, can be described in terms of the "map as a digital data base." However, as has been demonstrated for some time, all data bases for mapping do not have the same structuring requirements (Dueker 1987a) (e.g., map data bases that are used for spatial inventory [display only] are different from those used for spatial analysis). Since spatial analysis is the functional foundation of a GIS, along with capabilities for spatial data management, it follows that analytical map use coming from analytical cartography is also one of the roots of GIS.

Although analytical cartographic systems have employed coordinate data management strategies for some time (Peucker and Chrisman 1975), such systems do not use attribute data management techniques to the same extent as a GIS. Emphasis has always been on the geometry of space rather than the phenomenology of entities. However, even current GIS software architectures focus on spatial-data file management, not data-base management, at least in the sense that "data-base management" is described in computer-science literature with such functions as multiple sessions and rollback. However, we still claim that these are spatial data bases.

The main topic of this article concerns the use of virtual maps in terms of spatial data bases as models of reality. This follows the perspective of Board (1967), whereby a map was interpreted as a model of reality; but here a map is used for more than communication, it is also used for computation. However, as Sayer (1984) and Harley (1989) point out, we must be careful of whose interpretation of reality we use, and be conscious of the nature of the institutional-based reality represented. This issue is always at the backdrop of any discussion that deals with the use of a map as a model of reality, and has not been addressed in significant depth (except for Harley 1989), particularly from a realist theory (Bhaskar 1978). Since this article is about concepts and meaning, undoubtedly these issues will arise in the mind of the critical thinker. They are not treated here, but are treated elsewhere regarding geographical information in data bases (Nyerges 1991).

Although map use has been treated in many articles, to the author's knowledge the topic has not been treated from an analytical-cartography perspective. The next section considers analytical map-use issues by focusing on the current lack of analytical support for higher-order map-use tasks. Section 3 addresses the nature of the information content and structure required in an analytical map for higher-order map use. The support concerns operations that produce information from data content and structure. Finally, concluding remarks offer a perspective on the impact and direction of analytical cartography.

Map Use

Several cartographers have elucidated their concern with the nature of map use by examining the range of map-use tasks (Olson 1976; Morrison 1978; Board 1978, 1984). In a study of simple thematic maps, Olson (1976) recognized three distinct levels of map-use tasks, each successively more complex and demanding, but she focused on the first two (Figure 1). Level one involves comparing the characteristics of individual symbols: shape, relative size, importance (e.g., the difference in shape of a triangle and a square, or comparing sizes of two triangles). Level two involves recognizing properties of symbol-groups as a whole in terms of spatial pattern or likeness to other map patterns. A general assessment of simple and complex patterns is made. Level three involves using a map in a decision-making or content-knowledge-building manner through integration of symbols with their meaning. Symbol-referent relationships are fundamental in this context. Symbol differences and clusters are important, but only in the sense that they represent phenomena and their spatial (geographical) characteristics.

Through a study of map-use tasks for topographic maps, Morrison (1978) identified two groups of tasks,

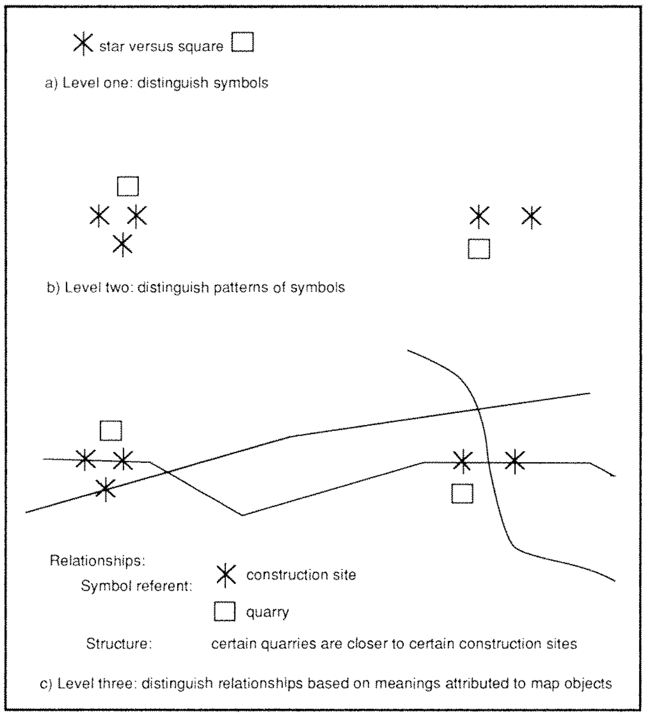

Figure 1. Levels for map-use tasks.

each consisting of several subtasks. One group of tasks includes detection, discrimination, and recognition that use subtasks for search, locate, identify, delimit, and verify. A second group includes estimation that uses subtasks for count, compare or contrast, and direct and indirect measurement. In the framework outlined by Olson (1976) all of those tasks are at levels one and two (i.e., no world referents are used to gain an understanding of how tasks are applied in certain contexts). However, Morrison noted that complex map-use tasks involve a combination of simpler tasks, but he did not elaborate on which simple tasks are used for which complex tasks.

Reviewing tasks appropriate for experiments in map use, Board (1978) identified three major types including navigation, measurement, and visualization. Navigation tasks involve movement from one place to another and include such subtasks as search, identify, and locate position on map, orient map, search for optimum route on map, search for and recognize landmarks along route, search for and identify destination, and verify. The measurement task includes subtasks for search, identify, count, compare, contrast, estimate, interpolate, and measure. The visualization task involves picturing mentally a terrain scene and includes subtasks search, identify, describe, compare/recognize, contrast, discriminate/distinguish, delimit, verify, generalize, prefer, and like (pattern).

Reassessing higher-order map-use tasks, Board (1984) elaborated on Olson's (1976) treatment of task ordering by pointing out that level one, abstract symbol interpretation tasks, are contained in level-two tasks, and level-two tasks are contained in level-three tasks. Furthermore, Board (1984) noticed that Olson (1976) discussed level-three tasks only briefly, perhaps because of the simple maps she chose for her study of map-use tasks.

To further elucidate the nature of higher-order (level three) map-use tasks, Board (1984, p. 86) went on to synthesize a list of generic geographical questions developed by Slater (1982), selecting questions of most significance for decision making and content-knowledge building. The questions, from simple to more complex, are listed in Table 2. Board condensed the specific questions into a general set of topics that involve 1) location and extent, 2) distribution and pattern, 3) spatial association, 4) spatial interaction, and 5) spatial change. Although the cross-reference between questions and topics was not presented by Board (1984), it is presented in Table 2 to help clarify the nature of questions that can be addressed.

How many of the questions of Table 2 have been, are, or should be solved as part of analytical cartography's contribution to GIS? Are we well on the way to addressing these questions, or are we faced with the prospect of forgetting, as pointed out by Board's (1978) title, "Higher-Order Map-Using Tasks: Geographical Lessons in Danger of Being Forgotten"? We are still using virtual maps primarily for locational-level questions, and only approaching the distribution and pattern-level questions at a rudimentary level in analytical systems, particularly in GIS. In most cases this is due either to 1) the institutionalized nature of the information being requested, 2) a lack of current capabilities in systems to provide information products, or 3) a lack of knowledge to put systems to use. The latter problem should not be underestimated, as it is an educational dilemma at the current time, and not a training problem (Nyerges and Chrisman 1989).

Questions being asked of makers of analytical maps need to refocus on tasks at level three in a more systematic way, regardless of whether they end up in spatial decision support systems or GIS (Densham and Goodchild 1989). Systems to perform higher-order analytical cartographic tasks are not new. Several systems, mostly related to transportation studies, have existed for some time with graphics and analysis components (Osleeb and Moellering 1976; Kornhauser 1977; Babin et al. 1982; Williams 1984). Unfortunately, these systems lack an efficient and effective data-management component, which limits their ability to be extended to address map-use questions for which they were not programmed.

Currently, software in a GIS consists primarily of graphics, data management, and analysis components. However, these components lack support for

Table 2. Geographical questions for decision-making and content-knowledge-building map use (adapted from Board 1984).

Questions dealing wih location and extent:
Where is the phenomenon of interest?
What is the phenomenon there?
Why is the phenomenon there?
How much of the phenomenon is there?
Questions dealing with distribution and pattern:
Is there regularity in the phenomenon distribution?
Where is a phenomenon in relation to a similar one?
What kind of distribution does the phenomenon make?
Where are the limits of the phenomenon?
Questions dealing with spatial association:
What other phenomena are there too?
Do phenomena usually occur together in the same area?
Questions dealing with spatial interaction:
Is the phenomenon linked to other phenomenon?
What is the nature of the phenomena linkage?
Questions dealing with spatial change:
Has the phenomenon always been there?
How has the phenomenon changed spatially through time?
What factors have influenced the spread of phenomena?

several tasks at level three because many of the constructs and/or the operations for answering decision-making and content-knowledge-building questions are missing. Current systems are able to work only on points, lines, areas, or surfaces (with their attendant attributes) as conceptually flat maps (Rhind 1988). The main issue in this article is how we can make such conceptual-information content and structure available more readily in a computational form to support higher-order, map-use tasks. This is similar to the issue Goodchild (1987a, 1987b) addressed concerning the development of next-generation, analysis-oriented, spatial-data models for GIS. However, further clarifications of the nature of the information content and structure, along with the operations at both the information and data levels of map use, are needed to continue systematic progress on these issues.

Virtual Map Content and Structure

Different map-use tasks require a different information content and structure; the real issue concerns the nature of information content and structure. A pertinent question to focus the discussion is: What geographical knowledge must be embedded in a cartographic data base for certain levels of analytical map use?

Information Content in Virtual Maps

After several years of experience with GIS, Goodchild (1987a, 1987b) concluded that information from analytical maps (as data bases) are delivered through a query mode by questioning a data base, or through a product mode such as maps, tables, or lists. A query mode usually is characterized by quick response and specific and well-known criteria. A product mode is characterized by a need for a large quantity of information with relatively broad criteria. Both of these modes are based on the current performance levels of systems, as well as standard, institutionalized modes for supplying information. However, equally restrictive is the capacity of the human mind to use the information for problem solving and decision making (Sowa 1984).

Miller (1956), followed by several others (Anderson 1983), have found that an average individual can hold seven, plus or minus two, chunks of information in short-term memory. A chunk is an amount of information that can be recognized and recalled from long-term memory. The basic property of a chunk is not its size, but its unity as a well-learned, familiar pattern (Sowa 1984). Consequently, single concepts as well as entire maps can be considered chunks of information (Head 1984). The nature of a chunk is dependent on how familiar a map user is with the spatial context of a problem, as well as how a chunk is used. Although the nature of chunking in map information is different, institutionalized modes for chunking do exist.

Query and product modes of output are convenient ways for delivering chunks of information in analytical systems (Goodchild 1987a), and are consistent with an ability of the human mind to process information sources at any given time. Whether higher-order map use-tasks take a query mode or a product mode depends on the nature of user requirements for information.

Special requirements of maps made for particular purposes have been known for some time. Board (1978) provided an outline of map-user requirements based on the nature of map-use tasks to be performed. This is related to data-base requirements identified through a systematic analysis of needs as part of a data-base design (Dangermond and Freedman 1984). Data-base requirements are data elements that must exist in a data base to satisfy a specific set of questions and tasks. Each map application, in terms of a set of tasks to be performed, has its special needs. The special needs of individual organizations (or parts thereof) result in the need for a specific data-base model. Each data-base model is used as the design framework for the implementation of a specific data base. It is a model for a specific data base, but it is not the data base itself. Information in data-base models is generally described in terms of data domains for theme, space, and time (Sinton 1978). The nature of available or derivable data for theme, space, and time constrain map use.

Virtual maps used as content-knowledge-building devices are woefully inadequate as a result of the lack of conceptual information. What kinds of content-knowledge is available in our current data bases to support higher-order tasks? Simplistically, using an example from transportation studies (Table 3) we can examine this question in terms of entity classes and object types commonly available for manipulation in current systems.

In this example, entity classes derived by transportation analysts refer to meaningful topic-oriented concepts, as classes or categories of real-world referents. The idea of an entity class is consistent with the formal definition for "entity" by the Task Force on Digital Cartographic Data Standards: "a real-world phenomenon that is not subdivided into phenomena of the same kind" (Morrison 1988, 24). Entity definitions, as well as the relationships between entities, are part of the conceptual information that must be stored or derived for higher-order tasks. The entity definitions are stored as entity types to distinguish them from object types. Entity types are real-world referents, whereas object types are the abstractions to be stored in the data base. The latter provide the explicit meaning for what data structure constructs are to be manipulated by a computer.

The nature of the thematic, spatial, and temporal characteristics of phenomena is determined by application contexts. Data needed for an inventory application are different from data needed for an analysis application; however, data for two kinds of analysis can also differ significantly. For example, a virtual map used as a statewide highway network for pavement maintenance requires detailed spatial data by mile point as well as temporal and thematic data suitable for maintenance analysis. In contrast, a virtual map of the same state highway network used for truck-travel forecasting requires less detailed spatial data, but requires other kinds of data for theme, such as commercial activity at origins and destinations. Thus, the requirements for data-base content, as well as structure, can differ widely by application. These requirements need to be balanced according to technical, economic, and institutional concerns (Dueker 1987b) when a data-base model is created.

A data-base model can be oriented to a project, application or, subject (Nyerges and Dueker 1988). A project data-base model is constrained to an individ-

Table 3. Entity classes and characteristic data domains.

information category as *entity class/type:*	examples from theme, space, and time *data domains*:
simple:	
roadway section	last surfacing at mile points
intersection	crosswalks last striped
district	area last funded for gravel
individual accidents	accident severity
complex:	
state route	mile-pointed roadway sections
state highway system	state routes
county highway system	county routes
1_Origin-n_Destinations	trip destinations for origin
political subdivision	jurisdictional hierarchies
clustered accidents	groups by space and severity

ual project undertaken at a particular time and is developed with a specific problem in mind. For example, an organization might be interested in developing a data set for rock quarries that service certain construction projects in certain transportation maintenance districts. An application data-base model usually serves any number of projects of a particular type; generally this constitutes such an application.

In another example, an organization might have want to identify all rock-quarry resources for any kind of use. A subject data-base model is developed with multiple applications, hence a multitude of projects in mind, and often develops out of integrating application data bases. Or, an organization might be interested in pavement conditions near all rock quarries and construction projects, because heavy trucks damage highways much faster than any other kind of vehicle.

In general, a subject data-base model can address more problems than an application data-base model, because of the variety of information represented. And, an application data-base model can address more problems than a project data-base model, because of the enhanced scope for any particular application. In many cases, a spatial analyst uses part of a data-base model to solve a particular problem, relying on a specific information structure composed of information chunks. An information structure is a mental structuring of simple and conceptual information chunks from a data-base model that is used for examining, hence understanding, particular geographical problems. It is important that a data-base model be well-defined and extendable so that certain information structures are available or can be made available in the model to support the needs of particular users.

Information Structures in Virtual Maps

An information structure is composed of a surface-structure component and a deep-structure component (Chomsky 1965; Nyerges 1980), also called surface level and concept level (Head 1984), respectively. Surface structure is the organization of simple information chunks immediately perceptible to a user of a map. The simple information chunks are the individual graphical symbols on a map display, as well as data-base elements stored in a data base. Deep structure is the organization of the simple chunks that often provides the meaning of the information chunks in surface structure. The deep structure contains the conceptual information, as the basis of meaning, as well as the various geographical relationships among chunks that form the basis of abstractions of reality.

Although Chomsky (1965) introduced the ideas of surface and deep structure in his transformational grammar for natural language, the interpretation of these concepts used here does not rely on Chomsky's conceptualization. A strict natural-language interpretation of the symbolic and conceptual structures in a map (Head 1984) is not necessary for a set of organizing principles for a map (Schlictmann 1984). Like the concepts of surface and deep knowledge in expert systems, the concepts of surface and deep structures in a map provide a framework for understanding the richness of mapped information in an information structure.

In a cognitive, semantic interpretation of any language structuring (graphic, data base, or otherwise), surface- and deep-information structures are based on many mental schemata. A single schema is composed of a rule or set of rules for organizing chunks of information (Chase and Simon 1973; Klatzky 1975). Mental schemata as conceptions for information structuring can be stored as data-base schemata in a computer system. However, the mental schemata and data-base schemata are probably of vastly different forms (Sowa 1984). We have many mental schemata for the mind and many data-base schemata for computer system data-base descriptions.

Mental schemata are used by analysts in the creation of a virtual map (data base) as part of the data-base design process, as well as by a map user who selects information to examine as part of map-use tasks. Many of these schemata are standard institutional conventions that provide a consistent perspective for an organization. The institutionalized mental schemata operate at different levels of structuring (Sowa 1984). They correspond to the different constructs in graphical, natural, and data-base language for surface and deep levels of information-chunk structuring. For chunks of surface structure on maps, schemata are rules that organize symbols as they appear individually on the map display and as they are stored individually in a data base. For deep-structure chunks, the schemata organize the conceptual information associated with the surface structure in terms of the meanings of data-base/knowledge-base elements and their geographical relationships.

Deep-structure information in a virtual map commonly takes the form of declarative and/or procedural information based on geographical relationships. Declarative information is commonly stored as structure. Procedural information is computed as structure (i.e., stored as a process in the form of steps to derive structure). Both kinds of information are useful for higher-order map-use tasks concerned with the map as a decision-making or content-knowledge-building device. The integration of symbols with other deep-structure information is very important.

Visual display symbols and simple data-base elements as surface structure are important, but take secondary significance to the deep-structure concepts. The deep-structure information is the basic meaning of spatial (geographical) phenomena, the relationships among phenomena (often providing part of the meaning), and the meanings of the relationships among phenomena (Nyerges 1991). Thus, the deep-structure information is critical in geographical problem solving with maps. It provides the epistemology for interpreting the meaning of the individual graphical/data-base symbols as well as for analyzing their relationships in terms of a spatial structure (Unwin 1981).

Representing Information Structures with Data Models

Information structuring in an analytical map used for higher-order tasks has not been dealt with comprehensively, and is still a topic of current research (Goodchild 1987a, 1987b). Information-structuring constructs for virtual maps involve entity classes and their attendant characteristics (i.e., the data domains that best describe a real-world referent). Analytical processing depends on the way entity classes are structured or derived in a data model (Nyerges 1980; Peuquet 1984; Goodchild 1987a, 1987b). A data model is a set of descriptive constructs, a set of operations on those constructs, and a set of constraints that apply to both the constructs themselves and the operations on those constructs (Codd 1981; ANSI/X3/SPARC 1978). The descriptive constructs are not semantically structured (i.e., not loaded with semantics). However, the constructs do have a semantic potential based on the way a designer 1) makes use of the constructs (i.e., loads categories of information into the data model in terms of an information structure), and 2) uses the set of operations that can manipulate the descriptive constructs. The quality control for the information content and structure that results is determined by the use of constraints.

A data-base model is an expression of one or more information structures consisting of entity classes/types. A map user works with chunks of information structures in the form of individual symbols or collections of symbols representing meaningful concepts on a map. Since the information-structure chunks are the semantics of a data base, the information-structuring constructs are at a different level of data description than are data-model constructs (Nyerges 1980).

Data-model constructs for spatial-data models are called object classes/types (Table 4). An object class is the set of objects stored as data in a data base, whereas an object type is a definition that is used to differentiate one object from another and one class from another. Object classes are implemented using program language and data-structure constructs, according to their type. In spatial-data management systems the object types are often fixed according to software design. Consequently, a data-base designer must chose among object types already available to create a data base as a model of reality.

In Table 4 the object classes/types refer to the kinds of mathematical, structural representations useful in characterizing corresponding entity classes/types for each row in the table. Each of the entity classes/types and object classes/types requires attendant characteristics in terms of theme, space, and possibly time for describing the full nature of the class and type. Entities as individual world referents and the corresponding data-base objects are the surface-structure component of the data base. Relationships among entities, and the corresponding relationships among data-base objects, are the deep-structure component of the data base.

All three levels of data description (i.e., information structure, object type, and data structure) exist simultaneously in an operational data-management system. Since a map user manipulates information structures in a data-base management system, he or she also causes data manipulation to occur at the data-model (object type) level and at the program-language (data/storage structure) level.

Work in data-base management standardization has elucidated two dimensions for levels of description, a point-of-view dimension (ANSI/X3/SPARC 1978) and an intention-extension dimension (ANSI/X3/SPARC 1986). These dimensions help clarify how information in maps can be described in terms of user perspective and meaning, respectively. The levels of data description discussed here (i.e., information structure, data model, and data structure) are treated in reference to the intention-extension dimension (ANSI/X3/SPARC 1986). Information-structure meaning is embedded in, and therefore carried by, a data-model schema. The data-base model, as an expression of one or more information structures for a specific data base, is represented by the entity classes and their specific definitions stored in a data dictionary.

Data-model object classes provide a flexible means for storing entity classes and data domains in information structures. Such structures can be defined by a data-base designer who does not have to be a programmer. The entity classes and data domains are stored in a data-base schema using object classes to express the nature of thematic-, spatial-, and temporal-data characteristics. This ability to define an analytical project data-base schema without the support of a programmer is significant for analytical data-base use, especially when the schema could be a part of an application or subject data-base schema.

Constructing information representations for sim-

Table 4. Information-structure constructs and data-model constructs.

	information structure construct(s) as *entity class(es)/type(s)*	data model construct(s) as *object class(es)/type(s)*
simple		
	roadway section	link/chain, node
	intersection	node
	district	simple polygon
complex:		
	state route	path
	trip	node-pairs, path (links)
	state highway system	network
	county highway system	network
	1_Origin-n_Destinations	tree(s)
	governmental districts	lattice (networked hierarchy)
	state route	path

ple entity classes is not too difficult in current systems, but for complex entity classes it is a different matter. The simple object types are common in most current spatial-data models. The complex object types, however, still prove to be somewhat difficult. The complex entities in Table 4 constitute entire data bases, which is why Goodchild (1987a, 1987b) suggests that tasks involving these constructs are likely to be product-oriented rather than query-oriented. However, if we are to make progress, manipulation of these should approach interactive query mode. In order to do this, object types must be rigorously organized for convenient and efficient processing.

The main difficulty in handling complex entities is the lack of a systematic approach to structural information abstraction in data models (Nyerges 1991). Levels of data description are different from levels of data abstraction (ANSI/X3/SPARC 1986). These two issues have been treated in the spatial-data handling literature as if they are the same thing. For example, the levels of data description discussed by Peuquet (1984) are treated as levels of data abstraction.

Data abstraction is an approach to hiding (suppressing but not eliminating) structural, operational, and/or behavioral detail in a data model (King 1989; Manola 1990). Structural, operational, and behavioral abstraction are significant to analytical data bases, but are different (Hull and King 1987; King 1989; Manola 1990). This is consistent with Goodchild's (1987a, 1987b) observation that paths, trees, and networks are needed in spatial analytical data bases, but they may get implemented in different ways. They may be implemented by structural abstractions stored explicitly as relationships, by operational abstractions processed as a collection of attributes for simple objects, or by behavioral abstractions as a combination of both. Structural abstraction involves semantic structure of object types. Operational abstraction involves control structure of object types. Behavioral abstraction involves a combination of structural and operation abstraction.

Many object types in spatial data bases are "structural abstractions" of the real-world referents, and are only as useful as the nature of the information captured in the abstraction. Structural abstractions are useful for introducing semantics into data-base systems. Such abstractions have been the central focus for research on semantic data models during the past 15 years (Hull and King 1987). Simple structural abstractions for points, lines, and polygons have always existed in analytical systems as manipulable objects, but complex abstractions have been treated as entire data bases rather than conceptual constructs. More investigation about the creation and storage of complex abstractions is needed.

Operational abstractions are useful for constructing objects that may have only a temporary existence. Operational abstractions have a basis in the work on abstract data types in programming languages (Liskov and Zilles 1974) because they focus on procedures, but can be differentiated from these because an abstract data type has a permanent existence. Some work on abstract data types has been done in cartography (Bouille 1976; Burton 1979; Cox et al. 1980), but has found its way into few commercially available systems.

The basis of object-oriented programming is behavioral abstraction, a combination of structural and operational abstraction. Object-oriented programming encourages reusable programming code that supports rapid prototyping. Behavioral abstraction is an active area of research in computer science dealing with object-oriented data-base systems (Kim and Lochovsky 1989). This is the kind of direction that might help the implementation of the object-pair type in the spatial-data model proposed by Goodchild (1987a, 1987b).

Using Information Structures in Higher-Order Map-Use Tasks

Queries are stated and products are generated in analytical systems as a result of such map-use questions as the ones enumerated in Table 2. A set of subtasks for addressing such questions are an important part of map use. Such subtasks are associated with commands for invoking operations on object types in a data model.

Goodchild (1987a, 1987b) described the lack of analytical operations for performing high-level spatial analysis as a consequence of a limited focus on simple object types. On the basis of that observation he outlined a set of operations for an ideal spatial analysis component in a GIS. These operations can

1. Analyze the attribute of a single class of objects as in conventional statistical analysis

2. Analyze one class of objects using locational and attribute information

3. Analyze the attributes of object-pairs

4. Analyze more than one class of objects

5. Create new object-pairs from one or two existing classes of objects

6. Create a new class of objects from one or more existing classes of objects (Goodchild 1987b, 72)

Those operations can be matched to the level-three questions listed in Section 2 to determine whether all the questions can be answered by Goodchild's (1987a) set of ideal operations (Table 5). The numbers in the left column of the table designate the operations listed previously.

Even the set of ideal operations has difficulty addressing all of the questions in Table 5, as indicated by the absence of operations for the last three questions. This suggests that even this set of operations is in need of enhancement, or that the questions are simply too difficult to ask of any system, or both. The last three questions that concern temporal aspects of data are beyond current systems in terms of reasonably efficient and effective solutions, but some research has begun to suggest the nature of the problems and solutions (Langran and Chrisman 1988; Langran 1989).

The set of questions listed in Table 5 do not represent all of the future potential for systems. Goodchild (1987a, 1987b) enumerated several complex problems that can be solved with his ideal set of operations that are not included in the set of issues listed by Board (1984). These are nearest neighbor analysis, spatial auto-correlation, spatial interaction modeling, network analysis, and polygon overlay. Of these tasks, polygon overlay has been a consistent offering in many systems although Goodchild (1987b) sees room for improvement. Network analysis usually comes as a separate module (i.e., as an add-on [Lupien et al. 1987]), but single origin and destination analysis is not sufficient to solve most transportation problems. Spatial interaction modeling is just beginning to be introduced into GIS (Caliper 1989), but it has been a standard feature in specialized transportation-analysis systems (Babin et al. 1982) for some time. Nearest neighbor and spatial auto-correlation have not found their way into any system to date, due to a lack of general understanding of the value of such methods for particular applications (Unwin 1981).

Conclusion

Many special-purpose, spatial-analytical systems with specialized modeling capabilities have been in place for some time (Moellering 1980). Most of them exist for pedagogical purposes in academic environments, but are not in mainstream use. This is further evidenced by the fact that research in spatial decision support systems is still in its infancy. Some systematic progress can be expected in the near future since spatial decision support systems are one of the research initiatives of the National Center for Geographic Information and Analysis (Densham and Goodchild 1989), but the effort will take more than a single research initiative for thorough exploration.

A dilemma exists in the use of analytical maps in content-knowledge-building and decision-making activities. These kinds of maps are the most specialized thematic maps that apply to the overall knowledge and interests of decision makers. The information structures are therefore complex, and tend to be problem specific. Such information structures for analysis require a high level of expressiveness and efficiency in system design, these criteria normally are satisfied as a trade-off between one another.

It follows then that one of the major constraints for social-science analysis in GIS has been data-model expressiveness and efficiency for the higher-level information constructs required by special-purpose analytical maps (i.e., those that explore higher-order questions). In today's systems support for higher-order map-use tasks requires expensive changes to data-modeling constructs because their functionality is

Table 5. Analytical operations matched to higher-order geographical questions.

Operation*	
	Questions dealing with distribution and pattern:
2	Is there regularity in the phenomenon distribution?
2,3	where is a phenomenon in relation to similar one?
2	What kind of distribution does the phenomenon make?
2	Where are the limits of the phenomenon?
	Questions dealing with spatial association:
2,4	What other phenomena are there too?
4	Do phenomena usually occur together in the same area?
	Questions dealing with spatial interaction:
4,5	Is the phenomenon linked to other phenomena?
	What is the nature of the phenomena linkage?
	Questions dealing with spatial change:
	Has the phenomenon always been there?
	How has the phenomenon changed spatially through time?
	What factors have influenced the spread of phenomena?

*Explanation given in the text.

changed at the programming level. An alternative is to design systems where data-model constructs (if sufficiently robust) get changed at the data-base design level, or use object-oriented programming languages that support reusable program code. Such systems would begin development of a social-science GIS, as most analytical thematic maps are created from social-science-oriented data that have conceptual structures more complex than point, line, and polygon. The mapping/GIS/spatial programs for social-science analysis have been useful, but they have stayed in the simple point, line, and polygon analysis closet for some time.

The data model outlined by Goodchild (1987a, 1987b) could be the beginning of a data-model framework for social-science analysis in GIS, but in a clearer sense it is another round of evolution for analytical cartography. Unfortunately, Goodchild (1987a, 1987b) suggested that his data model was not commercially viable. The viability of a market is determined by identification of customers through differentiation. Perhaps those organizations in need of such analyses are not easily identifiable as a market sector. However, we are beginning to see some commercial interest in such systems (e.g., TransCAD for the transportation community) (Caliper 1989). Transportation studies have always been a reasonably well-differentiated field of study, but even here it has taken some time.

The marketplace for social-science GIS, or an analytical cartography that has been applicable to social-science geography for some time, is difficult to identify. What is required is a better articulation of the needs in various application sectors, with more reflection on the major thrusts in geography, as well as more team research with public-sector agencies. Even in analytical cartography, we should not just constrain our focus to quantitative technique, for there does seem to be some promise for qualitative work as well, especially concerning conceptual processing (Sayer 1984). Such work is necessary to enrich the conceptual structures of analytical maps. To do this we need a concerted effort by groups of social scientists in order to progress; the complexity of the issues are beyond the expertise of any single individual.

It is hoped that this work will encourage others to look beyond the communication/analytical dichotomy. Although it is important to understand that there is room for maps as images and maps as computational tools, it is perhaps more important to understand that both are necessary to make maps more useful. Analytical cartography is not just for analytical cartographers, but for all who seek to explore the theme, space, and time of reality with more flexibility than ever before.

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