Formalizing Semantic Spaces For Information Access

Sara Irina Fabrikant* and Barbara P. Buttenfield**

*Department of Geography, University of California, Santa Barbara
**Department of Geography, University of Colorado, Boulder

An exponentially growing volume of digital information makes extraction of relevant items increasingly difficult. This article documents the adoption of information visualization tools by researchers in the disciplines of geography, computer science, and information science to facilitate exploration of very large data archives. Graphic depiction of database content (or the database "semantics") can be based on a spatial or even a geographic metaphor. Such depictions, often called information spaces or information worlds, provide one example of "spatialization." Various forms of spatialized views are critiqued in this article. To date, systematic approaches to the creation of spatialized views have lacked solid theoretical foundations. Three spatial frames of reference are presented to formalize and visualize semantic spatialized views: geographic space, cognitive space, and Benediktine space. Application to an example of a very large online catalog (GEOREF) highlights the underlying assumptions of the space types and demonstrates what spatial properties are preserved for each proposed approach. *Key Words: information retrieval, semantic information spaces, spatial metaphors, spatialization, visualization.*

> The summation of human experience is being expanded at a prodigious rate, and the means we use for threading through the consequent maze to the momentarily important item is the same as was used in the days of square-rigged ships. (Bush 1945, 102)

This statement, written half a century ago by the Director of the Office of Scientific Research and Development, has not lost relevance. On the contrary, the overwhelming volume of data makes it necessary to consider effective ways to locate, analyze, extract and digest information archived in proliferating digital repositories. This article explores the application of cognitive and spatial concepts to the exploration, navigation, and knowledge extraction of very large datasets, online archives, and digital libraries of geographic information, an issue that is critical to the development of geography in the Information Age. A broad range of research in geography can benefit from improved access to online information sources, especially areas that work with large data sets. As the volume of collected data increases, demands for improved access are also likely to increase. This research could be used to improve current digital information-seeking tools such as Yahoo, AltaVista, and other Internet search engines by including tools to provide an overview of available information, to discover relationships between items in a data archive, and to filter nonrelevant pieces of information. Timely and efficient access to relevant data facilitates knowledge acquisition, scientific endeavor, and research advance.

The National Research Council's Committee on Human Factors (NRC 1995, 202) identifies three major concerns regarding information access and usability. First, inefficient extraction methods challenge access to a relevant subset of information, if many unwanted items are retrieved. Second, incompatibilities between the user's and the system designer's mental model of a query often obstruct retrieval, if no items at all are returned. This is referred to as the "zero hit" problem. The third concern is the low level of user satisfaction expressed when significant items are missed or cannot be retrieved.

Information is a valuable commodity, and the seeking and retrieval of information have thus become critical activities in the Information Society (Marchionini 1995). In a data-rich environment, access becomes the bottleneck in information processing. Paradoxically, as data availability increases, access to relevant information becomes increasingly difficult (Buttenfield 1997). Often, the time gained by use of automated data collection procedures is lost through inefficient search and retrieval. Reorganization and graphical depiction of database content (or "semantics") can be based on a spatial or even a geographic metaphor (Card, Mackinlay, and Shneiderman 1999). These representations are called information spaces. To date, systematic approaches to apply spatial metaphors to information archives lack solid theoretical foundations.

This article documents the adoption of information organization and visualization tools by researchers in geography, computer science, and information science to facilitate exploration of very large data archives. Three spatial frames of reference are presented to formalize and visualize database content: geographic space, cognitive space, and Benediktine space. We define a frame of refer-

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ence as a perspective or an approach that one takes on to frame a solution to a particular application. A frame of reference emphasizes certain aspects of the solution or allows specific properties of the solution to emerge. In this case, application to an example of a very large online catalog (GEOREF) demonstrates that specific spatial properties are preserved for each proposed reference frame. These properties encapsulate the semantics of the represented data archive, and can be embedded in visual displays. Recent empirical testing indicates that the displays can help people to access data in online archives more effectively than do current text based query form interfaces containing alpha-numeric scrolling lists, keyword query boxes, and similar query tools.

From Information Retrieval to Knowledge Acquisition

Classical techniques for information retrieval focus on analytical search strategies, wherein the presence of an item of interest must be known in advance in order for that item to be found. Known-item searches require a set of explicit keywords, iterative query refinement, and the detection of relevant objects among retrieved results (Shneiderman 1998). A well-known problem is the so-called keyword barrier (Maudlin 1991). Keyword-based retrieval removes keywords from their surrounding context, and this may introduce ambiguities of meaning. Marchionini (1995) argues that traditional information retrieval techniques do not effectively handle synonymy (multiple terms describing the same object), polysemy (a single term carrying multiple meanings), anaphora (pronouns encapsulating clauses or an entire sentence), or metaphors and analogies (describing one concept in terms of another).

A conceptual shift has recently occurred within the field of information retrieval. The shift acknowledges that information seeking involves more than mere retrieval of relevant documents. Access is treated as a sense-making process (Dervin 1983) by which new knowledge may be acquired. Knowledge acquisition is viewed as fundamental to learning and problem solving (Marchionini 1995). Newer terms such as data mining, information grazing, and foraging reflect the acceptance that access and retrieval strategies must take into account high-level cognitive processes (Dervin 1983; Marchionini 1995; Pirolli and Card 1995). The shift brings about a broader approach to information acquisition. Central to the new approach is that the information seeker becomes the main actor; the information seeker and the context of the task become the center of investigation. System design is increasingly balanced by task-centered usability evaluation (Nielsen 1993a; Rubin 1994) and user-centered system design (Landauer 1995; Shneiderman 1998).

Spatial Information Access and Cognition

By analogy to Carbonell (Maudlin 1991, xv), the spatial information revolution is indeed upon us, although critical voices might argue that, instead of revolution, an era of information pollution has arrived. Rapid developments during the last two decades in information technology and the consequent impact upon society encourage a re-emphasis on cognitive research within the spatial data community. GIScientists have restructured approaches to spatial data, to information technology, and to its use. One emerging concern is the impact of spatial data handling methods upon various societal groups. Studies are proliferating on ways that organizations, groups, and individuals manipulate geographic information to model the world (UCGIS 1996). The authors of these studies place high priority on constructing less biased representations of geographic processes within data models, databases, and software (Mark and Frank 1991; Mark 1993; Medyckyj-Scott and Hearnshaw 1993; Mark and Freundschuh 1995). Researchers argue the importance of understanding how digital representations are understood by people utilizing GISystems (Turk 1994; Knapp 1995). Empirical studies demonstrate how decision making can change when graphical changes are introduced to those digital representations (Leitner 1997).

Cognition of geographic information is defined as one of ten research priorities by the University Consortium for Geographic Information Science (Montello 1996). The need for a general theory of spatial relationships and fundamental spatial concepts is not new to GIScience (NCGIA 1989; Goodchild 1999), but it has gained new importance in the past five to ten years due to wider usage of GIS tools outside geography.

Research on the cognition of geographic information has been identified as being important in decision making, planning, and other areas involving human-related activities in space (Medyckyj-Scott and Hearnshaw 1993; Frank and Kuhn 1995; Nyerges et al. 1995a, 1995b; Frank 1996). Research questions such as "How do people learn about geographic information?" or "How do people develop concepts and reason about geographical space?" beg for an interdisciplinary approach, drawing upon expertise in cognitive psychology, geographic information science, cartography, urban and environmental planning, and computer science. Understanding of spatial cognition can also be applied to nonspatial domains, facilitating information seeking and enhancing sense-making about retrieving data from very large archives.

Information Visualization and the Spatial Metaphor

Long before there was written language, there were pictures (Tufte 1983; Tversky 1995, 29). The emergence of scientific visualization in almost every discipline is grounded in the principle that physical and visual representations are easier to learn, understand, and communicate than are abstract numeric or textual information (Arnheim 1969; Tufte 1990). The long history of map design, as well as the more recent information graphics explosion (Tufte 1997) in science (McCormick, DeFanti, and Brown 1987) and the media (Monmonier 1989), are a result of the recognition of humanity's powerful ability for visual thinking, visual communication, and visual comprehension (MacEachren 1995). Even more recently, graphic depiction of information has also emerged within the field of Human Computer Interaction (HCI) as a mechanism to navigate and access information from vast databases (Shneiderman 1998). Examples include sophisticated designs for graphical user interfaces, visual access tools for large distributed data archives, graphical depictions of complex information networks, and the visualization of computer algorithm processing stages (Robertson, Card, and Mackinlay 1993; Ahlberg and Shneiderman 1994; Gershon and Brown 1996; Young 1996; Shneiderman 1998).

Spatial metaphors are applied commonly to visualize information, particularly to envision abstract, multidimensional concepts (Erickson 1993; Tilton and Andrews 1994). One very well known example is the desktop metaphor utilized to represent a computer operating and file system (e.g., Apple Macintosh's Finder). Another less well known metaphor mimics a digital "office" space with perspective view of walls filled with citation links, and hierarchical citation graphs that look like conic-shaped trees which serve as visual navigation aids for bibliographic searching (Robertson, Card, and Mackinlay 1993). In other examples, the spatial metaphor is explicitly geographic. Point-of-interest visualizations (Olsen et al. 1993), information landscapes (Chalmers 1993, 1995; Atkins 1995), populated information terrains (Carlsson and Hagsand 1993; Benford et al. 1994), fisheye views (Furnas 1986; Lamping, Rao, and Pirolli 1995), and space-scale diagrams (Furnas and Bederson 1995) are utilized to envision specific kinds of database structures and to afford visual information exploration. Multiscale diagrams also provide spatial metaphors for zoomable interfaces (Bederson and Hollan 1994) and visual hypermedia networks (Fairchild, Poltrock, and Furnas 1988; Nielsen 1993b; Mukherjea, Foley, and Hudson 1995; Hightower et al. 1998). A collection of documented examples can be found in Card, Mackinlay, and Shneiderman (1999) and at the Geography of Cyberspace Directory.[1] This site includes the Atlas of Cyberspace, maintained by the Center for Advanced Spatial Analysis (CASA) at University College London (Dodge 2000).

The intention behind using a spatial or geographic metaphor is to create a graphic representation that is ". . . accessible to human cognition . . ." (Skupin 1998, 1)—that is, to allow the viewer's intrinsic comfort with everyday concepts of human spatial orientation and wayfinding to guide their exploration and interpretation of the representation. Recent and highly promising application of geographic metaphors to very large online data catalogs (Wise et al. 1995; Skupin and Buttenfield 1996, 1997; Dolin 1998) demonstrates straightforward mathematics for construction. The method could also be applied to very large gazetteers of World Wide Web addresses (for example, the indices of AltaVista or Yahoo), or to any large collection of information that arranges items in a certain semantic or logical order.

Due to the need for cross-referencing, frequent updates, and maintaining and establishing linkages between items, large information archives can have complicated organizational structures. Graphic representations of archive structure have been shown to be equally complex (see Nielsen 1993b and Skupin 1998 for a number of examples). Couclelis (1998, 210) asserts that the geographic metaphor is the ". . . single richest, most systematic source of coherent submetaphors for structuring complex information representations."

Interestingly, the information science community commonly applies the term "information space" to label digital catalogs, gazetteers, and indexes to library collections and data archives, regardless of whether a spatial or geographic metaphor has been utilized to represent them. Couclelis (1998, 210) also notes that "It is well established by now that electronic information spaces can be designed to have virtual properties of empirical geographical spaces." The objective in creating a geographic analogy is to generate an information landscape based on experiential properties of the real world. The viewer's natural inclination is to explore unknown graphical terrain; by doing so, one browses the information collection. "System designers rely on users' natural curiosity to see what lies behind the panel, or in a cartographic metaphor, 'what's over the next hill' (Buttenfield and Weber 1994, 13)."

The term *spatialization* refers to both the creation of a graphic representation based on a spatial metaphor and the transformation that condenses large complex data domains into their essential components. Skupin and Buttenfield (1997, 117) define spatialization as ". . . the projection of elements of a high-dimensional information space into a low-dimensional, potentially experiential, representational space." Spatialization involves a mathematical transformation that creates a logically defined coordinate system for rearranging a set of data items or documents in an archive based on their content and functional relationships. The transformation may be constructed semantically (on the basis of item attributes), geometrically (on the basis of links or structural relationships between items), or a combination of both.

Some might argue that the spatialized coordinate system is arbitrary, and indeed the coordinates of any map projection are certainly arbitrary and in some cases difficult to understand. Nonetheless, they are useful for many cartometric tasks. In a spatialization, the concepts of distance, orientation, gradient, and so on are formalized on the basis of semantic or structural relationships. Semantic spatialization involves identification, selection, and classification of item attributes to be preserved in the spatialization, whereas structural or geometric spatialization preserves topological and structural relationships between items in the information space. It should be noted here that the difference between semantic and structural spatialization may not always be distinct. Functional relationships between documents in a collection can have both a semantic and structural component. For example, documents in a library archive can be organized semantically by grouping items that share similar content under the same index heading. These items may also structurally be located close to each other, if the item location system followed a sequential numerical classification system (such as, e.g., the Dewey Decimal System).

In a semantic spatialization, spatial properties preserve cognitive image schemata (see Table 1 for a list of spatial image schemata) and facilitate interpretation of the information space. Cognitive association is particularly relevant when experiential properties of geographic space are preserved. For example, the geographic property of place is cognitively associated with location and containment. Results of the empirical work described below demonstrate that the property is preserved in spatialization of a document archive. The geographic concept of route/barrier is associated with connection and sequence of items in the information space. The geographic concept of region is similar to the place concept, but extends it with cognitive associations for item centrality/periphery, item distribution and expansion, and so on (Couclelis 1998). Additional properties may also be preserved—for example, geographic distance (a metaphor for similarity), scale (hierarchies of detail), and arrangement (concentration and dispersion) (Fabrikant 2000b).

Computational methods for creating a spatialization are typically a variant of ordination. Ordination, derived from the German word *Ordnung* (arrangement, order), provides a powerful set of mathematical procedures for exploratory data analysis and hypothesis generation (Kent and Coker 1994). Ordination forms a long-standing basis for measurement and scaling of abstract concepts in perceptual psychology (Stevens 1946) and statistics, as well as in other scientific disciplines. For example, ordination is popularly used in ecology to solve a basic research question: how to best order a series of objects (e.g., species) that can be described by a given set of characteristics (Kent and Coker 1994). When applied to a temporal item attribute—for example, reordering of archaeological objects along a time axis—ordination is known as "seriation." Seriation has been applied in specifically graphical domains, as exemplified by Bertin's

Table 1. Image Schema and Their Application in Spatialization

Image Schema	Properties and Graphical Representation
Container	Containers have an interior, an exterior, and a boundary. Regions can be modeled as containers with a specific attribute, e.g., population density as shown in a choropleth map.
Surface	Continuous data are modeled on a surface, e.g., on contour maps and isopleth maps, block diagrams, prism maps, and so on. Surfaces afford horizontal motion.
Near-far	Features in a scene that are closer to the viewer are perceived to be more prominent than features farther away (e.g., fisheye views or logarithmic azimuthal map projections). Graphic zooming simulates the continuum of scale and provides cues for vertical and horizontal motion.
Verticality	Graduated bar graphs, prism maps, and interpolated surface maps communicate the concept of "more is up, and less is down."
Path	Flow maps depicting networks envision the "source-destination" concept.
Link	Topological views of space describe the connectivity and adjacency of geographic features. Landmarks and route segments structure navigation through space.
Center-periphery	Thiessen polygon maps delineate functional regions. Regions can form semantic hierarchies.

(1977) work on seriation in graphic information processing. Well-known ordination techniques include cluster analysis, factor analysis, and multidimensional scaling (MDS). Ordination determines an object's place in an *n*-dimensional space, depending on the quality and quantity of its attributes.

In general, ordination allows reduction of high volumes of data into smaller, manageable units, as a solution space with the lowest number of dimensions necessary to describe a complex phenomenon is easier to comprehend (Kent and Coker 1994, 162). It is important to note that data reduction by ordination does not just imply information loss, but—as the name suggests—provides a reordering or restructuring of the data with the aim of revealing its essential components and functional relationships.

Ordination's strengths include hypothesis generation and data exploration. However, these may also be argued to be its greatest weaknesses, in that many procedures provide neither statistical significance levels nor formal indices for quantifying and interpreting the dimensionality of a configuration. In semantic spatialization, the goal is not necessarily the identification and interpretation of axes in the information space or the quantification of its optimal dimensionality. Rather, the goal is to rearrange data so as to support information seeking and facilitate knowledge discovery. Facilitation occurs as a result of isolating smaller portions of an archive in order to identify one or more documents meeting a specific criteria set.

Although the potential benefits of spatialization are recognized and examples outside the GISciences are numerous, systematic attempts to evaluate their effectiveness empirically are scarce (Kuhn and Blumenthal 1996; Skupin and Buttenfield 1996; MacEachren 1998; Skupin 1998). Here lies a fruitful area for research. The GIScience community has the necessary set of perspectives to tackle such research. These perspectives include theoretical lenses of place, space, and scale, as well as visual, mathematical, and cognitive approaches to constructing geographic representations (National Research Council 1997, 28–29).

Assumptions and Properties of Spatialization

Before one can construct a spatialization, one must formalize basic assumptions underlying its purpose and intended use. Chalmers (1995) offers spatial, semantic, and social justifications relevant to the design of complex information spaces. His spatial argument is grounded in the principles of Gibson's (1979) ecological model of perception. Gibson introduces the term *affordances* to describe opportunities for a human to interact with items populating a cognized representation of the real world. Humans make sense of the environment by exploring and interacting with it, and thereby form a representation of the surrounding world. Chalmers (1995) argues that information spaces designed with affordances similar to a geographic environment will be easier to comprehend. Users can explore virtual information spaces in similar fashion to navigating in the real world. Chalmers (1995) stipulates that an information design should approximate the organization of the information seeker's mental model as closely as possible. His social assumption is that information seeking is an inherently collaborative task. The design of the information space should incorporate principles about how people interact and share information in their daily work, that is, the principles of social practice associated with the constructed representation. Bowker et al (1997, xiii) concur: ". . . [T]here is a great deal to learn . . . about how the contingent, messy, and emotional/political aspects of people's work and leisure are linked with new technological developments and visions."

Additionally, the properties to be preserved by the spatializing transformation must be considered. Downs (1997, 117) itemizes characteristics that distinguish a "spatially aware professional." A subset of these characteristics that seems relevant for spatialization includes understanding of:

- a logical geometry, based upon
- a formalized coordinate system, and
- a continuum of geographic scale.

Preservation of geometry permits exploration of relationships between items in the spatialized representation. A coordinate system permits determination of distance and direction, from which other spatial relationships (size, shape, density, arrangement) may be derived. The continuum of scale permits exploration of the information space at multiple levels of detail, creating the potential for hierarchical grouping of items, regionalization, and other types of generalization.

The Semantics of an Information Space

The following sections offer three spatial frames of reference to formalize semantic spatialization of large information spaces. The first reference frame is based in geography and emphasizes the morphological structure of an information space, including geometry, topology, and dimensionality. The second emphasizes cognitive science and highlights user interpretation of spatialized representations. The third, Benediktine space, is based on tenets of human-computer interaction (HCI) and emphasizes the preservation of item attributes and functional relationships between items in an information space. Following a discussion of the three proposed perspectives, an empirical example demonstrates their applicability to an actual data archive.

Geographic Space

One obvious origin for formalizing an information space is anchored in the physical laws of geographical space. A key aspect of geographic space is the continuum of scale, ranging from the footprint of a soil sample to the footprint of a continent. A very large information archive can be searched at multiple levels of granularity, ranging, for example, from the level of detail required to identify a particular keyword or image pattern in a document to the level of generality needed to overview a data warehouse of distributed document collections.

Defining an object's location in relation to other objects in space-time is an inherently geographical task. Locating an item in an archive forms the most elemental task in many information retrieval activities. The fundamental geographic notion that "no two things can occupy the same point in space and in time" (Golledge 1995, 31) is the basis for locating a geographic entity in space. This concept is a function of scale and operates only at the finest level of detail identified to be appropriate for a particular geographical analysis. Whereas the Empire State Building can be distinguished from the World Trade Center on a New York City tourist map, the two are indistinguishable on an air travel map of the world. Likewise, at the finest level of granularity in information seeking, no two items in an archive or database can occupy the same place in a library stack, or the same record in a database architecture (Codd 1970, 1979).

One aim of geographical analysis is the characterization of a phenomenon's position and spatial extent in relation to other phenomena. This forms a basis for the study of spatial context. The parallel in information retrieval is cross-referencing—that is, identifying archived items that are partially similar to two (or more) identified items. Absolute and relative positions of objects in space and time may change depending on the scale and the time frame. It is possible that items will be repositioned in an information archive over time, as new information becomes available or with culling and reorganization of existing content. Haggett (1983) defines a distribution's change in spatial extent over time as diffusion.

The following key spatial concepts are extracted from Dent (1999) and Golledge (1995). Golledge makes the point that simpler primitive concepts are combined to derive additional spatial concepts. Each has a parallel in the spatialized transformation of semantic content:

- *Identity.* Identity distinguishes between occurrences in a set, by assignment of a unique label, for example. Class and category are derived concepts for grouping and differentiating occurrences.
- *Location.* Location is a fundamental building block for many geographical key concepts. Location has spatial and temporal components. Location may be determined by relative or absolute methods.
- *Direction.* Direction can be derived from relative location. It depends on the system of reference that gives meaning to the concept of orientation.
- *Distance.* Distance is also dependent on the system of reference. Distance in geography is conventionally based on Cartesian measurement. However, a distance may also be interpreted as "proximity" or "similarity." Shape is derived by combining distance and direction. Combining location and distance allows formation of concepts of connectivity, linkage, and density and leads to the concept of a spatial network.
- *Magnitude.* This primitive concept forms the basis for the concept of frequency—how many occurrences exist in a particular location. Pattern is derived in a two-dimensional distribution and leads to concepts of dispersion, clustering, and concentration. In three dimensions, magnitude can be combined with location and distance to establish the higher order concepts of slope and gradient.
- *Scale.* Geographic scale relates to the resolution of items under study and the level of detail that may be applied. The nature of the inquiry and the phenomenon of interest set the scale, and scale in turn determines the degree of generalization. Human cognition varies with scale, ranging from personal-scale space with direct sensory interactions to larger-scale space, where direct sensory interaction might not be feasible.
- *Time or Change.* The concept of change expresses the dynamic nature of geographic processes. A dynamic process can be identified by rate, type, and direction of change. A dynamic system includes events occurring at a particular point in time, actors and their movements over periods of time, and periods of stagnation (states) when events occur over periods of time.

Preservation of geographic primitives in a spatialization allows interpretations about the content of the information space and places the transformation in a sound semantic framework. For example, one might examine a spatialized view on the basis of location, distance, scale, and time. Location gives a sense of document existence in the collection. Coupled with distance, two documents may be cross-referenced by a linear connecting transect (as shown in Figure 3, discussed later in the paper). Items falling along this transect may be characterized as being more similar to one item (endpoint) or the other. Documents within a given (radial) distance of a central location form clusters of related information. Clusters may be nested hierarchically.

Introducing the concept of scale, clusters can be explored at different levels of detail. One level of detail provides an overview of the entire information space. Other more detailed levels "zoom in" upon a specific theme or a specific document. In the geographic domain, one's distance from a landscape mitigates the level of details apparent in the land. Imagine, for example, viewing on foot and then viewing as from an airplane window. On foot one sees plants and trees. From the airplane window one might see colors and textures associated with different landcovers. In the information space, the scale-dependence of the view needs to change as well, to give the user a cue about how "close" they are to the information space and what levels of granularity will characterize their view of the data archive, from the collection as a whole to individual books and documents.

The time concept is inversely proportional to scale when navigating through an information space. The faster the traveling speed through the environment, the less detail can be absorbed. Time is also important when exploring the content of an information space. Similar to footprints in the sand, information seekers may leave search trails behind while browsing an information space. These search trajectories relate to query histories in traditional information retrieval. Information items might be repositioned on or off the "beaten track" for faster discovery or later retrieval. Dynamic feedback and responsiveness of features in the information space are essential for enforcing the experiential nature of the metaphor.

Cartographic design principles offer a sound representational strategy for visualizing geographic primitives (Bertin 1967, 1977; Tufte 1983, 1990, 1997). Cartographic abstraction plays a key role in mapping multivariate complex phenomena, where the map author selects, classifies, simplifies, and symbolizes the information content. This process, known as cartographic modeling, forms a fundamental aspect of geographic information processing. Abstraction and formalism give cartographic modeling its unique power, not only for visualization but also as an ideal instrument to organize, analyze, and communicate (Bertin 1967, 1977).

Cognitive Space

Knowledge about space is one of the earliest forms of knowledge that humans acquire (Taylor and Tversky 1996). Environmental learning and spatial knowledge acquisition research build upon developmental theories (Piaget and Inhelder 1967), involving transition from an egocentric pre-representational frame of reference through a topological, then a projective, and finally a metric frame that may be Euclidean (Golledge and Stimson 1997, 8–9). It is interaction in space, not perception of space, which is considered a fundamental building block for the acquisition of spatial knowledge (Golledge and Stimson 1997, 159). Taylor and Tversky (1996, 389) find that describing space is a relatively simple task that people perform well. They assert that humans organize space hierarchically, by salience, by function, or by relating elements at the top of the hierarchy to those lower in the hierarchy (Tversky 1995; Golledge and Stimson 1997).

Sensorimotor experiences with tabletop spaces[2] play one key role in how mental models are thought to be constructed (McNamara, Hardy, and Hirtle 1989; Diwadkar and McNamara 1997; Freundschuh and Egenhofer 1997; Roskos-Ewoldsen, McNamara, and Shelton 1998). Much of this work is based on the premise that spatial concepts are largely projected from human-body orientation (Howard and Templeton 1966; Lakoff and Johnson 1980). In contrast, Kuipers (1978) and other authors argue that large-scale environments, such as those experienced in everyday life, are not necessarily comprehended from a single mental viewpoint. In psychology, spatial footprints larger than two meters on a side that permit immersive navigation, such as a neighborhood, are characterized as large-scale. The exploration of large-scale space is connected to navigation and spatial wayfinding. In contrast to the tabletop cognitive domain, a large-scale cognized view is constructed in segments, with each segment describing a known route and newly introduced landmarks attached to segments. Taylor and Tversky (1996) suggest that environments that can be viewed from a single viewpoint are assimilated with a gaze tour, using a relative frame of reference (e.g., tabletop spaces or small rooms). Large-scale environments are described either by route (an intrinsic frame of reference) or by survey perspective (an extrinsic frame of reference). Perspectives can be switched frequently, and the choice is thought to be dependent on the type of environment and how the environment has been experienced—for example, by navigation or by map reading (Taylor and Tversky 1996). In a cognitive reference frame, geographic properties such as location, distance, and direction tend to be weakly defined (Mark and Frank 1996).

Cognitive space provides a useful perspective for representing information spaces, as shown in a diverse set of studies. Applications range from an artificial intelligence perspective (Kuipers 1982, 1983) to geographic preference (Lynch 1960; Gould and White 1974). Cognitive space is also used to frame spatial choice and geographic behavior (Golledge and Stimson 1987, 1997; Golledge 1992, 1995) and decision making (Mark and Frank 1991, 1996; Montello 1991, 1996; Mark 1992, 1993; Mark and Freundschuh 1995; Montello and Freundschuh 1995). Use of this approach in linguistics applies the cognitive metaphor to nonspatial concepts (Lakoff and Johnson 1980; Johnson 1987; Lakoff 1987). Lloyd (1997) summarizes numerous subject testing experiments linking cognized frameworks empirically to graphic and cartographic displays.

Egenhofer and Mark (1995, 4) propose the rubric "naive geography" to encapsulate the body of knowledge that people acquire about the surrounding geographic world. Naive geography formalizes how people think and reason about large-scale space. Egenhofer and Mark (1995, 7–11) present a collection of elements that contribute to such a geography, elements that would be important to consider when constructing a semantic spatialization adhering to a cognitive space approach:

- Multiple conceptualizations of the information space should be available to the viewer;
- Multiple levels of detail should be available as well;
- Topology as well as geometry should be preserved; and
- Distance measurements should be relative, local, and asymmetric.

Commonsense geographical knowledge is often inconsistent, imprecise, and frequently incorrect, but is nonetheless good enough (or what Lynch [1960] would probably call "sufficient") for functioning in a multidimensional world (Kuipers 1979; Egenhofer and Mark 1995). As formalized within naive geography, commonsense knowledge turns out to be quite difficult to preserve in a digital environment, and remains an unsolved graphical challenge, since most graphical depictions are based in Euclidean geometry. Accepting that the term "representation" may include graphical, digital, or cognitive manifestations, the following guidelines apply for spatialized representation based upon a cognitive frame of reference.

A representation defines objects and relations, and a correspondence between them (Kuipers 1979, 5). Representations of commonsense knowledge are established by linking body experiences with cognitive constructs (Lakoff and Johnson 1980; Johnson 1987; Lakoff 1987). In his "spatialization of form" hypothesis, Lakoff (1987, 283) maintains that image schema used in everyday language to organize geographic space may organize abstract concepts. Stemming from direct physical experience, spatial image schema contain an intuitively understood structure of their own. In addition, such schema generate metaphorical mappings to complex nonspatial concepts (Lakoff 1987, 276). In an information space, such examples might include "information in this area of the collection is highly concentrated" or "retrievals from this region of the collection are dropping." Johnson (1987, 426) defines seven spatial image schema that directly result from sensorimotor experience. Image schema operate at a level of mental organization which can change over time. Table 1 describes how a subset of Johnson's image schema can be spatialized and graphically depicted.

Spatial image schemata lie at the core of cognitive structures and form a basis for many less concrete domains (Lakoff and Johnson 1980). A cognitive perspective contributes to the spatialization of information spaces by enhancing interactions between an information seeker and the semantic content of the information space. It is important to avoid serious usability impediments when building a spatialization by attending to the ways that people acquire and use spatial information. If a user must learn an abstract spatial language and adapt to the mode of representation, then usability of the spatialization is greatly impaired. Instead, the system design should reflect user needs for reasoning about representations.

Benediktine Space

While formalizing the structure of cyberspace "a common mental geography"—Benedikt (1991, 2) utilizes five essential topological building blocks of physical space (dimensionality, continuity, curvature, density and limits) to map any object into an abstract information space. The term *cyberspace*, coined by Gibson (1984), stems from the Greek word "kybernan" (to steer, to control) and implicitly links a spatial construct with a computing system. Properties of Benediktine space are inherently semantic; selected properties are also alluded to in the frames of reference of geography and cognitive science just discussed. Any particular point in a cyberspace defines an element's or phenomenon's location according to its own properties and in relation to the properties of the other elements populating the space. The following principles, extracted from Benedikt (1991, 132–224), formalize the nature of cyberspace.

- *Exclusion*. No two objects can share the same place at the same time.
- *Maximal Exclusion*. An object's extrinsic dimensions should be chosen so as to minimize violations of the principle of exclusion. Typical extrinsic dimensions are the *x-y-z* coordinates in Cartesian space, as well as time (a fourth dimension).
- *Scale*. The maximum velocity of user motion in cyberspace is an inverse monotonic function of the complexity of the world visible to the viewer (Benedikt 1991, 162). This principle relates to the different levels of detail representing an information space. The more dense the information display, the more slowly the viewer will have to move through it to grasp its content.
- *Transit*. Travel between two locations should occur through all intervening points. In addition, movement between locations includes a cost function that is proportional to some measure of distance. In the semantic metaphor, this is in accordance with Tobler's (1970, 236) well-known First Geographical Law: "Everything is related to everything else, but near things are more related than distant things." The principle of transit also includes the distinction between destinational data and navigational data. Destinational data represent objects populating an information landscape. Navigational data could be interpreted as metadata, to describe the data path between two data objects in cyberspace.

A Benediktine space can have multiple dimensions, depending on the number of attributes that describe an element. A phenomenon described by three variables (e.g., a person's age, height, and weight) can be mapped into a Cartesian coordinate space. However, it becomes problematic to visualize more than three dimensions concurrently, and to collapse multiple dimensions into fewer dimensions without crushing the rich semantics from the information. Benedikt attaches meaning to dimensions by encoding intrinsic and extrinsic properties into the representation. One can classify extrinsic properties to preserve the principles of exclusion and maximal exclusion, using, for example, an alphanumeric encoding, chronological ordering, or—as strongly argued in this article—a spatial arrangement.

Summarizing the Three Reference Frames

All three of the perspectives outlined above build upon principles of inquiry and representation applied by geographers and cartographers for many centuries. Principles building upon concepts of location and proximity, distance and direction, orientation and navigation, scale and region appear explicitly or implicitly in each reference frame. The commonality of elements is striking and should encourage the GIScience community to bring its geographic expertise to address problems of organizing very large collections of information, abstract concepts, and user orientation in very large online data archives.

It may be helpful to distinguish the three approaches in terms of the spatial metaphors that underlie their representations (Table 2). Each reference frame introduces a sense of sequence to the applied spatial metaphor. It is notable, however, that the focus of each perspective is unique. The geographic reference frame focuses upon measured environmental structure based on geometry, topology, and dimensionality. The primary objective in the cognitive reference frame is not upon measurement, but on spatial commonsense knowledge, spatial knowledge acquisition, and learning. The Benediktine approach focuses upon the preservation of semantics in the information space (e.g., item properties and functional relationships). Particular attention in this reference frame is directed to activities (such as transit) upon the transformation and to how well the morphology reflects

Table 2. Spatial Metaphors Underlying Representations in Different Spatial Frames of Reference

Spatial Frame of Reference	Metaphors
Geographic space	Representing a phenomenon's semantic structure with a metaphor that is based on an experiential, locational ordering principle. Real-world concepts of distance, direction, magnitude (height), and so on take on a semantic (functional) association. Generalizing the representation to maximal 3D (plus time) modifies the level of semantic detail apparent in the view.
Cognitive space	Tailoring or refining the representation in order to simplify the phenomenon's semantic complexity and to facilitate use and user comprehension. The refinement is based on viewer expectations about spatial relationships in geographic space.
Benediktine space	Transforming or reducing a phenomenon's multidimensional semantic dimensions into a lower dimensional representation (e.g., a Cartesian coordinate system). The transformation preserves the semantics of a phenomenon's attributes and the semantics of relationships between phenomena, permitting associations between motion (transit) and semantic content.

content, and less attention is paid to the precision of the structure itself.

Benedikt's reference frame extends the other two with inclusion of activity and motion. The transit concept provides capacity for movement through the spatialized view. Movement can operate on several levels. Information seekers can traverse the information space, literally immersing themselves in the information landscape, as discussed earlier in the geographic perspective. On another level, the Benedikt approach makes it possible to consider flows of content across an information space, to consider metaphors of semantic rivers or highways through an archive, to mark these routes for navigation, and to monitor the information collection for impedances in those flows. These characteristics of Benediktine space have been shown to establish a quickly adopted rapport with users in recent subject testing, as described below (Fabrikant 2000b). For this reason, the Benediktine frame of reference will receive special attention in the remainder of this article.

Graphic Depiction of Spatialized Views

The transformation underlying all three types of spatializations converts semantic content into spatial structure by means of some type of ordination, for example, nonmetric multidimensional scaling (Osgood, Suci, and Tannenbaum 1957; Kent and Coker 1994) or self-organizing map (SOM) algorithms based on neural nets (Kohonen 1997; Oja and Kaski 1999). Many rely upon Salton's (1989) vector space theory to quantify keyword comparisons. This method creates an inventory of keywords, or attributes, for all items and generates a vector identifying which keywords are present or absent for each item. Keyword vectors can be generated using existing collection thesauri or indices, or can be extracted automatically from full-text documents, through latent semantic indexing algorithms, for example (Furnas et al. 1988). Vectors are numerically compared to generate a matrix of item similarities. The similarity matrix forms the input to a multidimensional scaling procedure. A detailed articulation of the computations is beyond the scope of this article but is fully presented in Skupin and Buttenfield (1996, 1997) and Skupin (1998).

Computing the spatialized transformation will reorganize the information catalog, gazetteer, or index, but this is not sufficient by itself to provide access to the information. The completion of the spatial metaphor lies in cartographic depiction. Principles for cartographical depiction of point symbols and for terrain surface depiction are extensive (see, for example, Imhof 1982; Dent 1999). Empirical research describing user responses to cartographic depiction of geographic phenomena is clearly described in the cartographic literature (Medyckyj-Scott and Board 1991). It is notable that the Benediktine reference frame is spatial but not necessarily geographical, while the representational strategies are explicitly geographical. A geographic representation is a subset of a spatial representation, targeting information about the

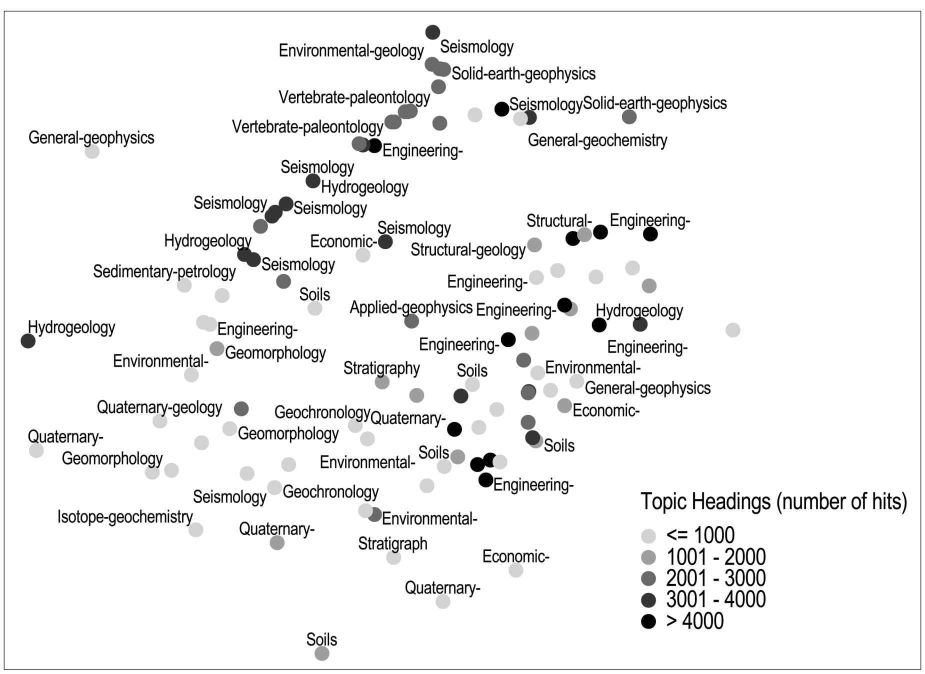


Figure 1. Document spatialization in 2D, at high level of detail (modified from Fabrikant 2000b).

Earth. As such, it must include specific geographical characteristics such as adherence to the rules of gravity and the existence of a very wide range of available levels of detail (from the microcosms to the macrocosms), where content and structural aspects of the represented features tend to change with changing resolution. Spatial autocorrelation is another geographic property. The goal of a spatialization is not only to depict the aforementioned characteristics for the phenomena to be spatialized, but also to preserve them in the semantic transformation process. Common strategies in the Benedikt approach include point scatters (Dolin 1998; Skupin 1998) and landscape-like terrain models (Wise et al. 1995; Fabrikant and Buttenfield 1997; Skupin and Buttenfield 1997).

A spatialization of one hundred text documents is shown in Figure 1. The documents were extracted from the much larger GEOREF database, an online catalog of references for literature in the geological sciences. Document labels are their first-level keyword assignments from GEOREF's thesaurus. The shades of gray indicate how many other documents in the entire GEOREF database contain the same keyword. An information seeker can interact with and traverse this information space, creating graphical opportunities for real-time fly-throughs and direct manipulation. Utilizing a true three-dimensional data model, it becomes feasible to turn a point scatter around or upside down and thus to literally see the information collection inside out.

Figure 2 depicts the same data as shown in Figure 1, but at a lower level of detail. In this generalized spatialization, individual documents have clustered to semantic regions, or topical themes. The surface represents the topical breadth and depth of the GEOREF database. The higher the surface elevation, the more documents belong to a particular theme. Three theme examples are labeled in Figure 2. Theme labels are topic index terms taken from the GEOREF thesaurus. Details on how these spatializations were constructed are outlined in the next section.

The novelty of this perspective can generate new insights into the data collection. In similar fashion, using Gore's (1998) digital Earth metaphor, geographical insights can be gained from viewing a very large digital model of a house, of a virtual town, or even of a digital planet, by manipulating it, walking around it, or walking through it.

As stated earlier in this article, little empirical research has reported on or compared user response to Benediktine-style spatialized views. Thus, it is difficult to predict how well the geographical metaphor extends to representation of information, except to note that Benedikt intends that his frame of reference be applied to nonspatial domains. Surmising from Lakoff (1987), the

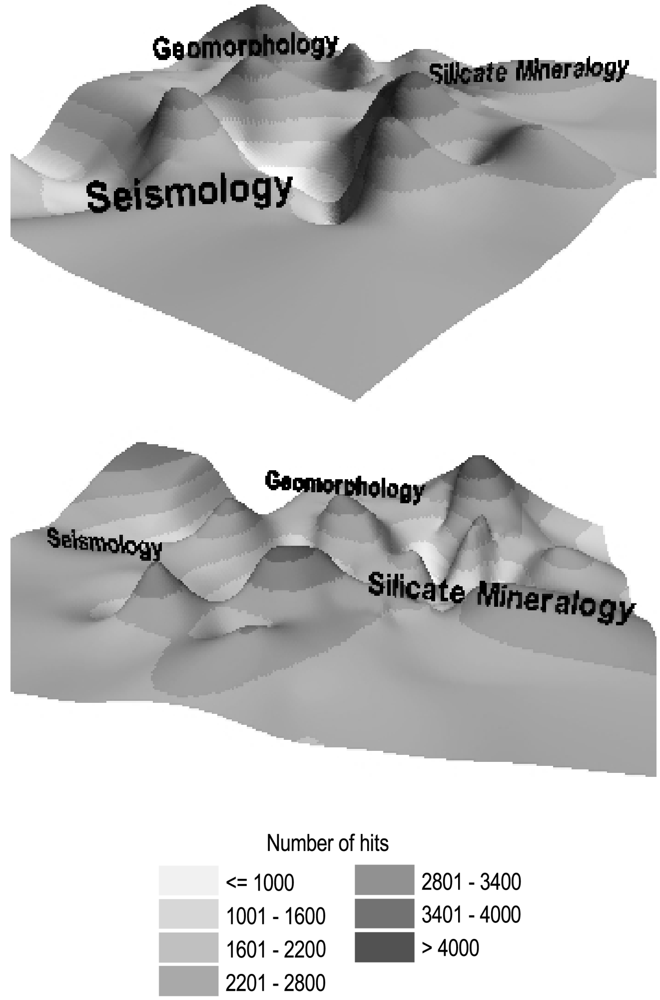


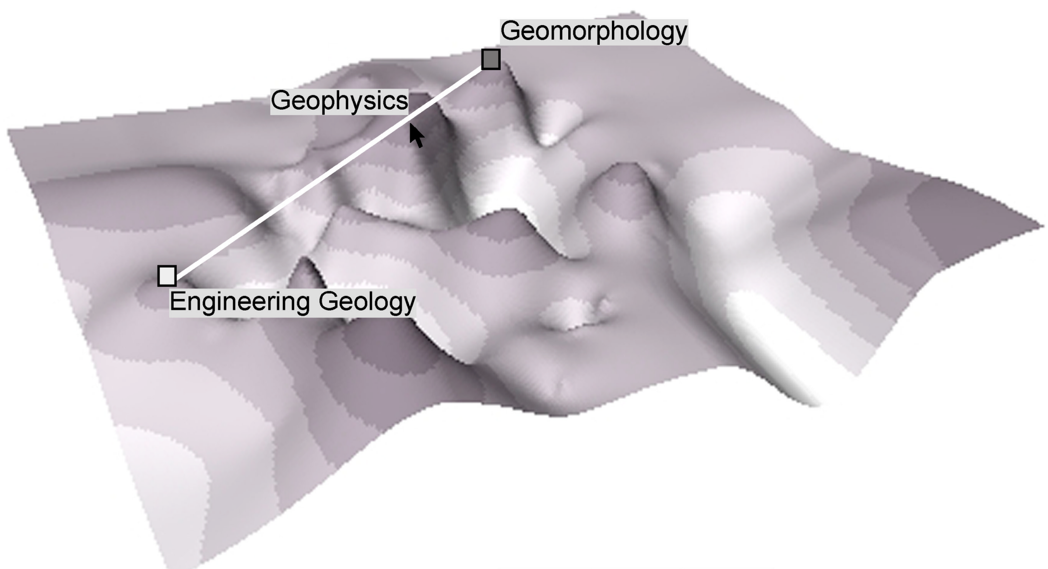
Figure 2. Overview of a 3D document information space from two different vantage points (modified from Fabrikant 2000b).

expectation is that the metaphor should cross over readily into nonspatial realms. In experiments in the Meridian research lab at Colorado, we constructed true three-dimensional graphical direct-manipulation depictions of an information space. Interesting participant reactions resulted from qualitative evaluation. Participants were told at the beginning of the test sessions that the landscapes were not a representation of geographic terrain, but of a library archive. Comments such as "it is shorter to hike from the valley to this mountain than to that one over there" or "oh, the sun has just gone down" (reacting to the addition of relief shading in the view) clearly indicate that test participants were responding to test questions as if they were exploring a real world environment. There were other striking reactions when test subjects suddenly comprehended that the virtual object they were "holding" was in fact not terrain, or a map of terrain, but an information archive—essentially a card catalog. Being able to manipulate an entire card catalog as easily as one would turn over a toy block turns out to be a very empowering experience.

Spatialization Example—A Digital Library Archive

Examples in the context of a digital library will be described to illustrate spatialized views of a semantic information space. For example, one can create a spatialization of a library card catalog, in which each book, journal, government publication, each dataset on CD-ROM, each video, record, map, and so on occupies a unique point location. The metaphor taken from the geographic approach focuses on location, distance and other geographic primitives. The location of a document can be assigned by its physical location in a library (absolute location) or by its proximity to other books (relative location).

Figure 3 illustrates a spatialized view for the same portion of GEOREF shown previously in Figures 1 and 2. Benediktine interpretations incorporate many similarities with the other two reference frames. In this figure, document locations have been mapped into the spatialized view by assigning an x-y coordinate pair according to a semantic rule. The rule is formalized on the basis of keywords taken from each document's GEOREF record description. Following Salton's vector space model (Salton 1989; Skupin and Buttenfield 1996, 1997), a document/keyword matrix was created from a subset of the GEOREF database. The matrix contained rows of documents and their corresponding keyword vectors in columns. The alphanumeric keyword vectors were transformed into binary vectors, where 0 represented absence of a particular keyword and 1 represented its presence from a total set of *n* possible keywords. The binary keyword array was then treated with the squared Euclidean distance measure, which resulted in a symmetric document-by-document output matrix containing proximity measures between the documents based on keyword cooccurrence. The more keywords documents have in common, the stronger is their semantic proximity. In other words, the stronger the semantic proximity between documents, the smaller the Euclidean distance between them. The square similarity matrix was input into ALSCAL (Young and Lewyckyj 1987), a MDS application based on the *Al*ternating *L*east Square *SCAL*ing procedure. For visualization purposes, only two- and three-dimensional MDS solutions were utilized. ALSCAL provides locational coordinates for each document in the solution space. These coordinate pairs or triples can be easily imported into a geographic information system (GIS) for further analysis and visualization. A detailed description of the GEOREF spatialization goes beyond the scope of this article, but can be found in Fabrikant (2000b).



4488	4488	4485
4487	4490	4484
4485	4480	4480

Figure 3. Visual browsing of the GEOREF information space (modified from Fabrikant 2000b).

Other semantic rules to map document content could assign coordinates on the basis of meta-information stored in MARC records, a table of contents, or subject index, or even by full text parsing. Additionally, semantic rules can be applied to map document usage patterns. Each would result in a somewhat different spatialization, as discussed below.

In the context of Benediktine space, a coordinate pair is assigned by mapping intrinsic dimensions (keywords associated with the document content) to destinational data objects (*x* and *y* coordinates). Coordinate assignments are defined such that documents that are close have similar sets of keywords, following after the method of Salton's (1989) vector space model. Benedikt's properties of exclusion, maximal exclusion, scale, and transit are preserved.

Metaphors from the cognitive viewpoint build upon and facilitate the geographical metaphors. The cognitive expectation that distance is associated with similarity is evident in that items in the spatialized view that are proximal are more similar than are distant items. Subject testing at the Meridian Lab verifies that spatialized views preserve this cognitive expectation, and also determines that color enhances the association (Fabrikant 2000b, 115). Another cognitive expectation is that taller things have greater magnitude ("bigger" means "more") and utilize a third dimension in the spatialized view. For instance, height in the spatialization could represent the number of times an item has been accessed, the density or strength of document association (derived by a clustering algorithm [Wise et al. 1995]), or (as shown in the figures) the frequency of documents characterized by a common set of keywords (Skupin 1998). In effect, hills identify locations in this information space where similar items are dense enough to "pile up" into smaller and larger "information landforms." Fabrikant's (2000b, 115) experiments indicate that ". . . people associate graphic clusters [in the spatialized view] with concentration of related documents."

The GEOREF spatialization can be represented by alternate spatialized views, including a point scatter in which each point identifies a document (see Figure 1 for an illustration), an isoplethic map, or—as shown in Figures 2 and 3—a landscape, implying that the points have clustered so closely together as to form a solid information surface. It appears that the alternative views are appropriate to specific searching tasks. In subject testing, Fabrikant (2000b) determined that the landscape view is well suited to initial (overview) browsing. The isopleth view appears to provide test subjects clearest associations to identify clusters of similar documents.

Navigational data (Benedikt's term for the path between two documents in the spatialized view) are also meaningful. A transect line connects two regions of the information space (as shown in Figure 3, connecting the topic of geomorphology with the topic of engineering geology). Transit along this line follows a path of cross-referencing the GEOREF collection. Keywords for documents located along this transect are semantically associated with the keywords for endpoints. The semantic association with a particular endpoint increases as one moves closer to that endpoint. One could conceivably construct a set of distance-cost functions for this GEOREF landscape, describing the navigational paths for different search strategies to access particular documents. Alternatives could include document availability, document diversity (the number of keywords), document types, and so on.

One could expand the transit concept and use the structure of the spatialized view as potential metainformation about semantic content. In analogy to the remote sensing technique that distinguishes features on the basis of their spectral signatures, one could derive *semantic signatures* that describe and distinguish types of documents that comprise an information space. Buttenfield (1984, 79–82; 1986, 497–98; 1987; 1989, 97; 1991, 152) uses the same spectral analogy to derive and implement *structure signatures*, which are graphical depictions of changes to the geometry of a geographic feature resolved across multiple levels of resolution. Her work demonstrates that such signatures provide statistically significant methods to distinguish differences in feature geomorphology. Other geographic examples include morphometric analyses based on fractal structure, self-similarity, and self-organization signatures of fluvial landscapes (Rodriquez-Iturbe and Rinaldo 1997). Semantic signatures could be derived from the organizing structure of the view or by monitoring navigational paths an information explorer follows while browsing the information space. A specific organizational structure might reveal a distinct pattern within the collection. Depending on the chosen classification scheme—such as Library of Congress, Dewey Decimal, ISBN, and so on—a digital library's landscape morphology might vary considerably. The signature could provide useful information to the information seeker as well as to the people maintaining the collection. Algorithms for pattern recognition of semantic content in digital libraries (referred to as content-based searching) have been developed for multimedia documents (Ma and Manjunath 1996a, 1996b; Manjunath and Ma 1996; Chandrasekaran et al. 1997; Deng and Manjunath 1997; Castelli et al. 1998), but full implementation remains a pressing research challenge for digital library research. Clustering based on similarity of wavelet transform signatures that describe image textures have also been applied to digital imagery stored in geolibraries (Ma and Manjunath 1996b; Sheikholeslami, Zhang, and Bian 1999).

Empirical Findings

Additional findings from Meridian Lab experiments indicate that, zooming into the landscape view, subjects learn to inspect a portion of the GEOREF collection in greater detail, eventually zooming into a resolution where individual documents separate in the graphical display. In the Benediktine approach, as described previously, transit speed and level of apparent detail are inversely related. At finer resolutions, where individual documents become the apparent focus of attention, the symbolization scheme of the spatialized view needs to change to emphasize individual items as opposed to groupings of items. Point scatter symbolization provides a more appropriate spatialized view, and participants appear to understand that in the spatialized view (contrary to geographic terrain) a continuous "landscape" (Figure 2) breaks down into individual documents at the finest levels of resolution (Figure 1).

Subjects react positively to the point scatter when their assigned task is to identify individual items, although, as Fabrikant (2000b, 115) notes, "for some [information displays] it takes longer to make a decision." This finding suggests that adding structural information to the graphical display might improve user reactions. Connecting lines added between points to create a node-link topology might help to reveal structure at higher levels of detail. Documents could take the form of landmarks, and connecting paths between them emphasize the type of functional relationships that exist between documents. The type and shape of the network topology might reveal additional structural information of the archive. Spatializations depicting a network of directional information flow patterns could be based on the intensity of cross-referencing. Cross-referencing intensity may be described as the magnitude of similarity in document content or as the amount of cross-citations among documents. Tracking of information seeker navigation could also be considered. GIScientists can perform such kinds of network analyses with standard, off-the-shelf GISystems.

In the landscape view, regions of the information space can be labeled to identify categories of holdings. At finer resolutions, labels may be attached to individual documents. Algorithms for automated name placement should be readily applicable to these types of scale-dependent labeling operations, once rules are formalized for delineating information regions in spatialized views (Skupin 1998). One may conclude from these studies that multiple spatialized views (graphical depictions) can be associated with a single spatialization (a single transformation of semantic content). Moreover, empirical results suggest that sound principles of cartographic design can and should be applied, to support the spatial metaphor for users (Fabrikant 2000b).

Conclusions and Future Work

This article documents current trends in information archival and access and acknowledges the increasing problems of access accompanying the information explosion. The use of geographical metaphors provides a viable avenue to overcome some access problems. Three reference frames are presented to provide a sound theoretical basis for current spatialization research. GIScience has much to add to the information representation conversation. As noted by the National Research Council (1997, 40), the formalization of a language for visual geographic representations and the inquiry on human cognitive representations of space comprise two important geographic research fields. As suggested in this article, these perspectives can be transferred to the nonspatial domain.

Skupin and Buttenfield (1996, 616) point to the absence of empirical evidence supporting the usability of spatialized views. Proof-of-concept demonstrations have been verified using subject testing procedures to exploit the full potential of spatialization. Recent empirical work to prototype and evaluate an interface design based on the principles described in this article demonstrates that users work effectively with numerous aspects of the spatial metaphor (Fabrikant and Buttenfield 1997; Fabrikant 2000a, 2000b). Full deployment cannot proceed solely on the basis of system design; it requires usability evaluation as well.

In terms of fully operational implementation, technological challenges are important to consider and include comprehensive tools for immersive virtual reality and for direct manipulation of items and objects in the spatialized views. Current research is underway to explore the potential of virtual reality technology for immersive spatialization. An interdisciplinary team of researchers from GIScience, psychology/cognitive science, and information science are creating an experimental testbed of an immersive information world to represent the National Imagery and Mapping Agency (NIMA)'s vast data collections. Design and usability evaluation of the immersive spatialization are ongoing at the Research Unit on

Spatial Cognition and Choice (RUSCC) of the University of California at Santa Barbara and at the State University of New York at Buffalo. The promise and potential of applying geographical metaphors to access information from very large archives cannot be ignored, especially given the increasing difficulties with access as the volumes of available information proliferate at accelerating rates.

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Notes

1. Available on the Web at http://www.cybergeography.org/geography_of_cyberspace.html (last accessed June 2000).
2. Psychologists refer to spatial footprints less than two meters on a side as tabletop, or small-scale.

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Correspondence: Department of Geography, 3611 Ellison, University of California, Santa Barbara, CA 93106-4060, e-mail: sara@geog.ucsb.edu (Fabrikant); Department of Geography, Campus Box 260, University of Colorado, Boulder, CO 80309, e-mail: babs@colorado.edu (Buttenfield).