CHAPTER 4.2

Perspective: Geographical Information Systems

Cyrus Shahabi[1] **and Shuping Jia**[1,2]
[1]*University of Southern California Brain Project and Computer Science Department*
University of Southern California, Los Angeles, California
[2]*Intuit Inc., San Diego, California*

Abstract

The goal of neuroscience research is to understand the structure and function of brains in general and the human brain in particular. We use a brain atlas as a standard for each species to consolidate data from different researchers. In order to achieve this objective, a spatial structure of the brain atlas as well as a standard coordinate system need to be defined. Similar challenges have been addressed in the area of the Geographical Information System (GIS); however, because of the differences between brain atlases and geographical atlases, some of the solutions proposed by GIS cannot be directly applied to neuroscience. In this chapter, we discuss some of the distinctions between brain and geographical atlases and describe our approach to tackle the challenges resulting from these differences.

4.2.1 Introduction

The emergence of neuroinformatics as a discipline has prompted the need for a standardization and coordination of neuroanatomical terminology and coordinate systems. These are cornerstones of effective information sharing among scientists and applications. At present, brain atlases provide the main practical standardized global maps of neural tissue. In this regard, the USC Brain Project uses the Swanson atlas (Swanson, 1992, 1993) as a standard to consolidate neuroscience data on the rat, which includes neuroanatomical and neurochemical data, time-series data, and publications.

As a direct result of the interconnection and consolidation of neural data, many neuroinformatic navigation scenarios will become feasible. For example, a neuroscientist can start data navigation from a repository of digital publications, select a paper, and then request to zoom into the Swanson atlas to see the corresponding brain section discussed in the experimental section of the paper. Alternatively, one might start from navigating the Swanson atlas and then request to view all the publications available linking certain research protocols to a specific brain region. Similar navigation can be initiated from a time-series data repository or a database containing neurochemical experiments; however, our concern is much more general, and the approaches we develop can apply to other atlases of the rat brain—such as the Paxinos-Watson atlas (Paxinos and Watson, 1986) or to comprehensive atlases of the brains of other species. While noting this generality, we nonetheless focus on the rat brain and the Swanson atlas for this chapter.

In order to employ the Swanson atlas as a standard to consolidate data from different applications, one should be able to relate each piece of data to a region on the brain atlas. This can be achieved in two steps:

1. Construct a spatial structure for the brain atlas.
2. Identify a standard coordinate in order to "map" data to the defined spatial structure of the atlas.

Similar issues have been addressed by the Geographical Information Systems (GIS) to map data on geographical atlases (Bekkers, 1998; Goodchild *et al.*, 1996; Guttman, 1984; Poage, 1998); however, due to inherited differences between brain atlases and geographical atlases, the solutions proposed by GIS are not directly useful for neuroscience applications. In particular, GIS usually replaces the circular globe by a series of flat maps where the relationship between these "sheets" is one either of adjacency or overlap. By contrast, the brain is an inherently three-dimensional structure so that the notion of adjacency of sheets or "levels" (as termed in the Swanson atlas) is different, as will be logically characterized in this chapter.

In this chapter, we first provide an overview of the state of the art in GIS. Subsequently, we discuss what GIS has to teach neuroinformatics, both indicating what we have done at USCBP, as well as the promises and pitfalls. Finally, we conclude by summarizing the main GIS techniques that NeuARt has used and those that look promising for the future extensions. At the end, we also provide an itemized list of URLs where one can find useful GIS material.

4.2.2 Overview of GIS

There are several different definitions for a Geographical Information System (GIS), depending on the type of user and the application domain (Medeiros and Pires, 1994). We start with the definition provided by Goodchild (1991) as "a digital information system whose records are somehow geographically referenced." From a database perspective, GIS manages *georeferenced* data. Georeferenced data consists of data elements whose locations are spatially referenced to the Earth (Carter, 1989). Three different data types are usually managed by GIS: (1) conventional record-based data consisting of alphanumeric attributes, (2) image (or *raster*) data, and (3) spatial (or *vector*) data. We focus our attention on raster and spatial data.

Raster Data

Raster data are simply a bitmap that, if displayed, illustrate the image of an area. Raster data are tightly related to what is called *field* view (Medeiros and Pires, 1994) or *space* view (Guting, 1994). This view sees the world as a continuous surface (layer) and is used to describe the entire space and every point in it; however, if the space consists of several objects, there exists no information on the location of these objects and their spatial relationships. For that, we need the vector or spatial data (see the following subsection). Raster data are useful to represent continuous phenomena such as atmospheric pressure.

Spatial Data

Spatial data are the data representing objects in space with identity, well-defined extents, locations, and relationships (Guting, 1994). The database system managing spatial data is called a spatial database system, which is typically an extension of a regular database system with additional capabilities to handle spatial data such as spatial data models, query languages, spatial index structures (e.g., R-Trees; see Guttman, 1984)), and support for spatial joins. Spatial objects are typically modeled as points, lines (or curves), and polygons. (Note that several other constructs such as networks and partitions are also discussed in the literature [for example, see Guting, 1994], but their descriptions are beyond the scope of this chapter.) A point represents only the location of an object, but not its extent or shape (e.g., a Zip Code area may be modeled by the latitude and longitude of its center). A line (can be represented by the coordinates of its two endpoints or can be a curve consisting of multiple line segments or a curve modeled as a spline curve represented by its parameters, or...) represents moving through space or connections in space (e.g., roads, rivers, cables). A polygon (or region) represents an object with extent and shape (e.g., city, Zip Code area). Fig. 1 depicts one approach to store different spatial data types as conventional records in a database (ARC/INFO, 1991). However, with recent advances in object-relational database management systems (OR-DBMS), a database can be extended to support spatial data types as first-class residents of the database system. Examples are Oracle 8i's spatial cartridge, the NCR TOR spatial UDT/UDF, and Informix Geodetic spatial datablade. These systems have data types such as points or polygons predefined and hence can be used by the user applications and/or SQL3 query language directly. Moreover, most of the commercial systems define special cases of polygon objects such as circles and rectangles as additional spatial data types.

Besides the representation illustrated in Fig. 1, there is an alternative way to represent polygons and arcs within ARC/INFO. This representation relies on the following three major concepts: (1) connectivity, (2) area, and (3) contiguity. We consider each concept in turn.

1. *Connectivity:* The *x,y* pairs along each arc define the shape of the arc. The endpoints of an arc are called nodes. Each arc can only have two nodes. Arcs can meet only at their endpoints. By tracking all the arcs that meet

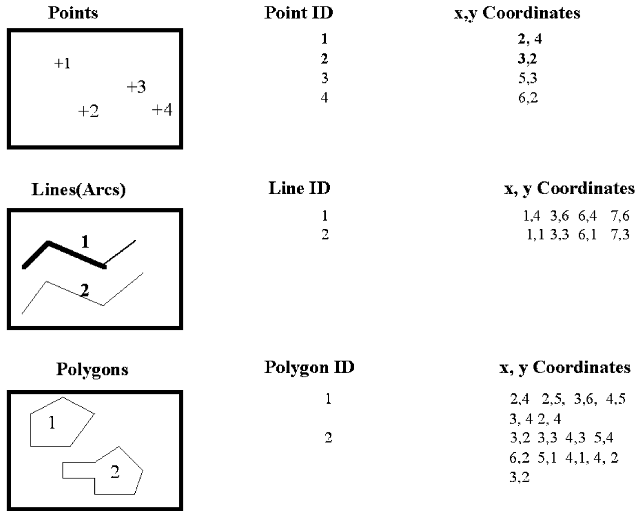

Figure 1 Multiple data types using the vector data structure in ARC/INFO. (From ARC/INFO (1991). *User Guide*.)

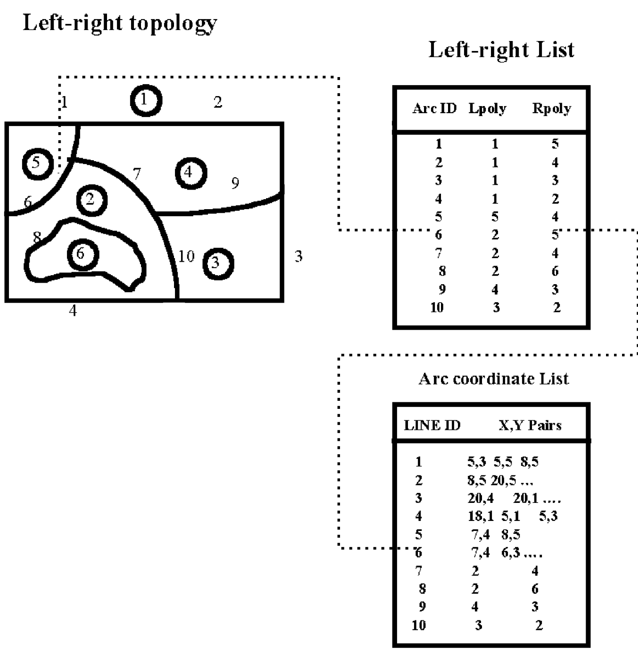

Figure 2 Contiguity. Circled numbers are polygon IDs; regular ones are arc IDs. (From ARC/INFO (1991). *User Guide*.)

at any endpoints, we can identify which arcs are connected.

2. *Area definition:* Polygons can be represented as a set of arcs instead of a closed loop of *x,y* coordinates. A list of the arcs that make up a polygon is stored and used to construct the polygon when necessary.

3. *Contiguity:* Two polygons sharing a common arc are adjacent. If a standard direction is imposed on every arc, then for each arc one can list the polygons on its left and right (see Fig. 2).

Spatial Relationships

One of the major reasons for storing data in spatial format is for later querying and accessing this data through spatial queries. These queries can be submitted either through a graphical user interface (for example, by interacting with a map-based GUI) or through utilization of SQL3 queries. The spatial queries typically look for specific spatial relationships between a query object and the objects in the database. Theses spatial relationships can be categorized into three types (Guting, 1994):

1. *Topological relationships:* These represent those spatial relationships that are invariant under topological transformations (i.e., rotation, scale, and translation). Between two polygon objects (or connected areas with no holes) there exist six of such relations (Egenhofer and Herrings, 1990): disjoint, overlap (or intersect), touch (or meet), inside, cover, and equal. The same concept can be extended for other spatial data types. For example, two points can only be disjoint or equal. Almost all of the commercial spatial database systems (e.g., extended OR-DBMSs) support all these topological relationships.

2. *Direction relationships:* Here, we are interested in finding the objects that satisfy a certain location in space with respect to a query object. These include relations such as above, below, north of, southwest of. There are two approaches to support direction relationships: project-based (Frank, 1992) and cone-based (Pequet and Ci-Xiang, 1994). With the former, a plane is partitioned into subpartitions, and the direction relation between two objects is identified by the subpartitions they occupy. With the latter, the plane is divided into five partitions that define the primitive direction relations (see Fig. 3).

3. *Metric relationships:* These represent the relationships that can be quantified such as "distance < 1000."

Now, a sample window query might be "Find all the theaters within 2 miles of my house." To support this query, the system needs to examine for "inside" relationships between coordinates of theaters (i.e., latitude and longitude) in the database and the circle defined by the user, with its center being the user's home address and the radius being the 2-mile distance.

Fig. 4 illustrates a sample GUI to query for average households color-coded within different states. The user can zoom in and out or change directions by clicking on the menu buttons.

Layers, Data Features or Coverages

The common requirement to access data on the basis of one or more classes of phenomena has resulted in several GISs employing organizational schemes in which all data of a particular level of classification such as roads, rivers, or vegetation types are grouped into so-called "*feature planes*", "*layers*", or "*coverages*" (ARC/INFO, 1991; Burrough and McDonnell, 1998; Jones,

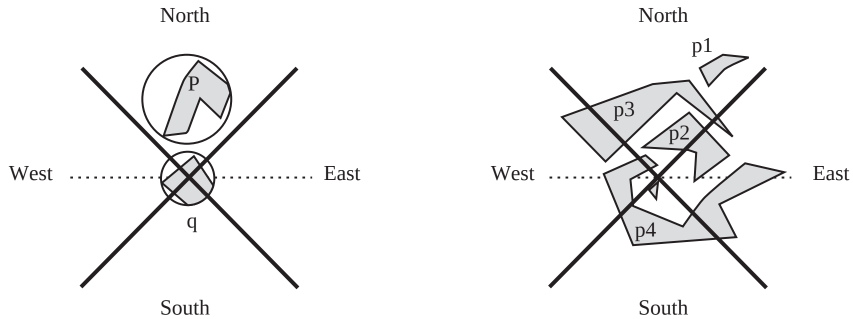

Figure 3 Cone-based direction relationships when objects spanning one or more direction(s).

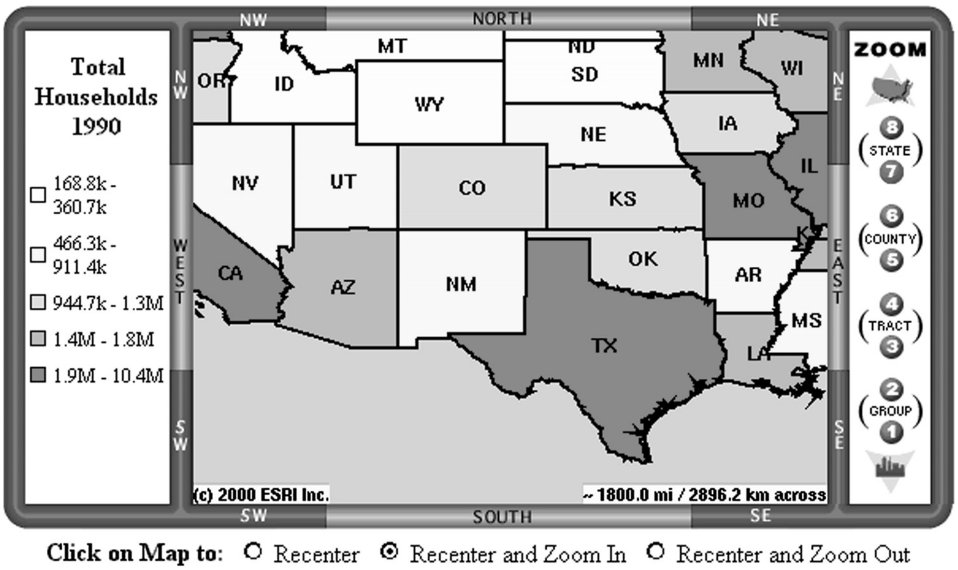

Figure 4 A GIS GUI for submitting spatial queries. (From http://www. esri.com/data/online/tiger/index.html.)

1997). In order to avoid confusion between this concept and the concept of "layers" used in the Swanson atlas, hitherto we will use the term *coverage* in this chapter.

Coverage represents the main method for storing vector data. A coverage is a digital version of a single map sheet and generally describes one type of the map spatial data, such as streets, parcels, soil units, wells, or forest stands. A coverage contains both the location data and thematic attributes for spatial data types in a given area. Coverage logically organizes spatial data into layers or themes of information. A base map can be organized into layers such as streams, soils, wells, administrative boundaries, and so on. A coverage consists of topologically linked spatial data and their associated descriptive data.

A coverage is stored as a set of spatial data types such as points, arcs (or lines), and polygons. The combination of spatial data present in a coverage depends upon the geographical phenomena to be represented. One approach to store information about a coverage in a database is as follows (ARC/INFO, 1991). Each arc record contains the arc's ID, location, and shape information defined as a series of x,y coordinates. Furthermore, for each arc record we can store the IDs of the polygons on its left and right, assuming that the coverage contains polygon features and a direction can be imposed on each arc. Subsequently, each polygon record contains a list of all the arcs defining the boundary of the polygon. No coordinates are explicitly stored for polygons, which means the polygons are stored topologically (Fig. 5 illustrates this representation).

The power of a coverage lies in the relation between the spatial data and tabular (descriptive) data. The important characteristics of this relation are:

1. A one-to-one relationship exists between data types that appear in the coverage and corresponding records representing the data type (e.g., x,y coordinates of a point data type).
2. The link between the data types within a coverage and their corresponding records is maintained through unique identifiers assigned to each data element.

Fig. 6 depicts several coverages, each of which is composed of numerous spatial data, superimposed on a single map sheet. The full system is available for interaction and download on the Web at the following URL: http://www.esri.com/data/online/tiger/index.html.

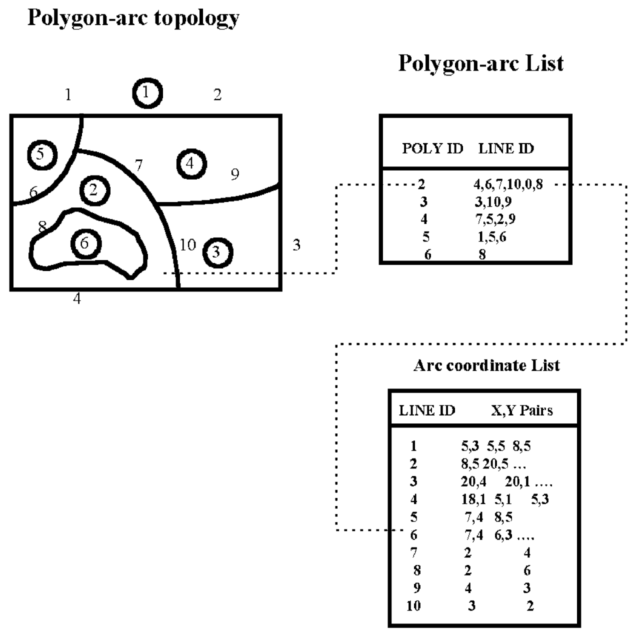

Figure 5 Polygon-arc topology. Circled numbers are polygon IDs; regular ones are arc IDs. (From ARC/INFO (1991). *User Guide*.)

The figure illustrates four coverages consisting of line data types—roads, railroads, transportation, and utility lines—and three coverages consisting of area data types:

1. Statistical boundaries, such as census tracts and blocks
2. Local government boundaries, such as places and counties
3. Administrative boundaries, such as congressional and school districts

The figure also shows three coverages of point data types:

1. Point landmarks, such as schools and churches
2. Area landmarks, such as parks and cemeteries
3. Key geographic locations, such as apartment buildings and factories

Registration and Rectification

Thus far, we used the term "coordinates" as a standard way to represent a point. These coordinates with GIS are the geographic coordinates of the point or its latitude and longitude. The latitude and longitude values for any point on the Earth are fixed for a given referencing system. In GIS, rectification and registration are

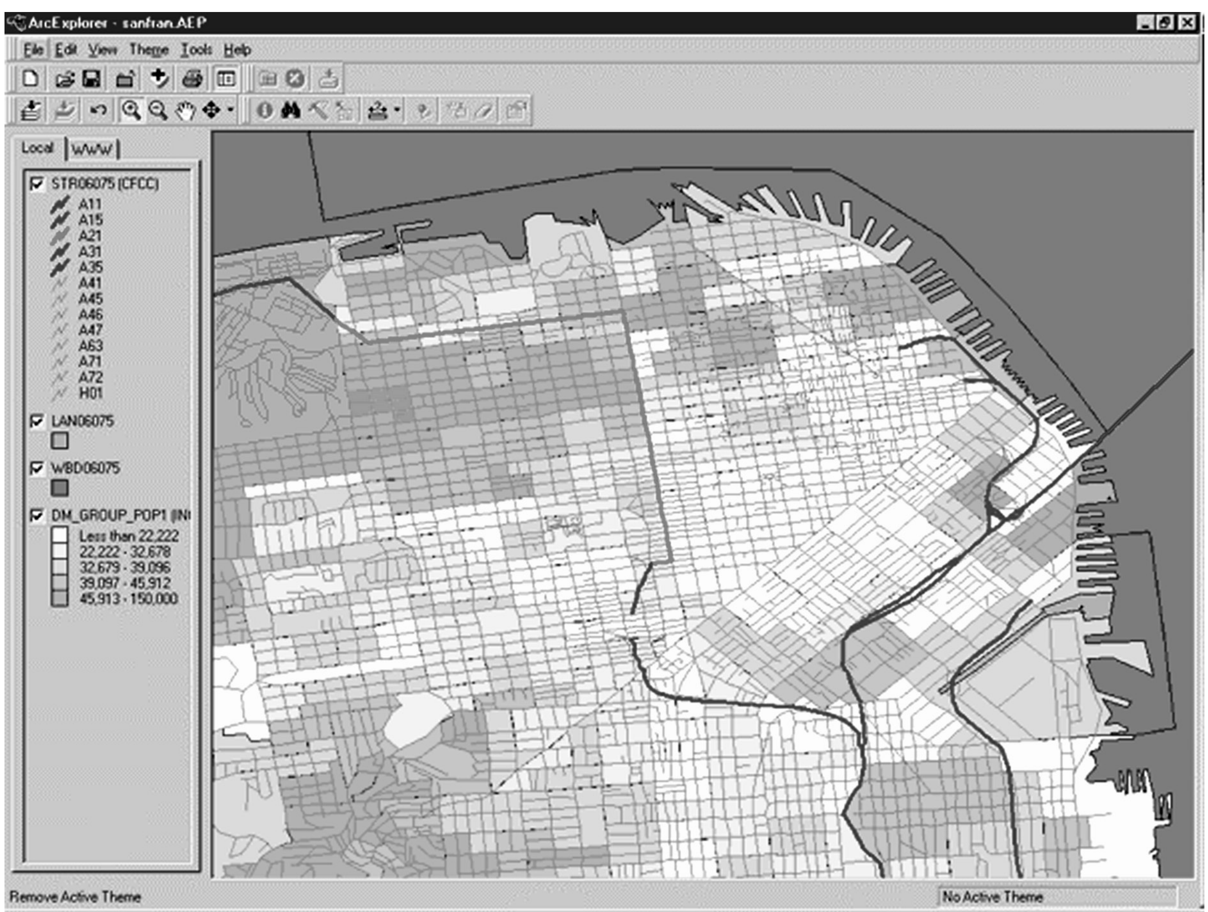

Figure 6 Several coverages superimposed on a single map. (From http://mapserver2.esri.com/cgi-bin/usdemog? m=3 & cd=5.)

based on a family of mathematical tools that are used to modify the spatial arrangement of objects in a data set into some other spatial arrangement (Goodchild *et al.*, 1996). Their purpose is to modify these geometrical relationships without substantively changing the contents of the data itself. Rectification involves manipulating the raw data set so that the spatial arrangement of objects in the data corresponds to a specific geocoding system. For example, a rough sketch of an undeveloped lot, made on-site by a landscape architect, typically does not show objects in their true spatial relationships. Once the sketch has been brought back into the office, the sketch can be re-drafted (perhaps as an overlay on a reproduction of an existing map that shows legal boundaries and easements) so it conforms to a useful coordinate system. Registration is similar to rectification; however, it is not based on an absolute georeferencing scheme. Both sketches from a field team and uncontrolled aerial photography have distorted views of the Earth's surface. The registration process involves changing one of the views of surface spatial relationships to agree with the other, regardless of any particular geodetic referencing system.

Generally, we do not have an exact solution to the problem of rectification and registration, either because we do not know the details of the map projection in the datasets, or because the data do not conform to a standard projection or georeferencing system. An example of the latter situation may be found in an oblique aerial photograph, in which the changes in scale across the image are due to the particular configuration of platform altitude, camera system alignment, and topography. A common approach, based on statistical operations, is called a *ground control point rectification/registration*. In this technique, locations of objects in the source data (often based on the arbitrary reference grid of raster row and column) are compared to their locations on a trustworthy map. A statistical model is then used to convert the data into a new set, with the desired geometrical characteristics.

An alternative procedure, often called a *rubber sheeting operation*, is as follows. Suppose we start with an uncontrolled off-nadir air photograph. This image will have many kinds of distortion due to aircraft motion, perspective problems contributed by the curvature of the Earth, scale changes due to topography, distortions in the camera lens, and so on. Next, we place the film over a "correct" map of the Earth, selected based on the desired map projection and scale. Subsequently, we identify a location on the map that is easy to distinguish on the image and run a pin vertically through the location on the images, down to the corresponding location on the map. This fixes the first location on the film to the corresponding location on the map. Finally, we identify another unambiguous location, place a pin through the photograph at this point, and run the pin down to the corresponding point on the map. The identified image points that have been attached to the map are the ground control points or tie points, and the number of points required depends on the geometric properties of both the desired map projection as well as the images. This rectification/registration process involves building a numerical coordinate transformation between the original image coordinates and the rectified (or "true") coordinates. Frequently, these transformations are based on polynomials, whose coefficients are computed by regression on the coordinates.

4.2.3 Atlas-Based Neuroscientific Data

The Swanson atlas was prepared from a rat brain sectioned in the coronal (frontal or traverse) plane. From 556 serial sections, 73 levels were chosen and illustrated as representative of the entire rat brain. Each brain is divided into regions and then further subdivided into subcortical nuclei and cortical areas. Neuroanatomical descriptions may use standard three-dimensional coordinates relative to a prominent landmark, but they are much more likely to be described by their approximate, relative position to the borders and small-scale detail of the structures that are contained in the region of interest. The plane of section of every experimental brain is different, so some coordinate transformation (or "re-slicing") must be applied to the data in order to map from an experimental brain section onto an atlas drawing (see Chapter 4.1 of this volume for more information).

Each level of the Swanson atlas captures the major cell groups of the rat brain, along with their subdivisions. The atlas gross structure hierarchy consists of: gross segments, segments, region, cell groups and fiber-tracts, and parts, from most general to most specific. For example, the septal region consists of the medial septal nucleus, the lateral septal nucleus, and the septohippocampal nucleus. These structures are related to each other in the same level by subclassing and/or adjacency relationships. Adjacency relationships describe which structures have common boundaries (Swanson, 1992, 1993). It is also important to note that structures in the atlas typically exist in more than one adjacent level (for example, the lateral septal nucleus exists on 12 levels) and that the same structure is typically bounded on more than one side. Because they are complex shapes, each structure can have few or many boundary structures (adjacency relations).

Several types of data can be placed over the atlas levels in order to summarize the results of experimental work in a systematic way (see Chapter 4.3 for examples and figures). Each experiment consists of several tract fibers, conceptualized as a layer superimposed on top of its corresponding atlas level.

In essence, the collection of atlas levels and the data layers is intended to illustrate the major cell groups and fiber tracts of the rat brain that can be identified with the

Nissl stain, which shows the distribution of cells in a histological section. It is analogous to a conventional geographical atlas that summarizes the distribution of water and land masses, along with the borders of countries at a particular time in history. Such maps are quite useful because they can be used as templates for plotting many other types of information: highway systems, population densities, energy production and distribution systems, and so on. However, with the passage of time, political boundaries change, and the amount of information available to plot continues to increase. Thus, the atlas templates (or levels) themselves will change over time. For the remainder of this section, we discuss an approach to represent the atlas levels and data layers within a spatial database system, in order to utilize the available GIS tools as much as possible for their management.

4.2.4 Raster Data

Originally, both the atlas levels and the experimental data layers were only two stacks of two-dimensional images. We still do store the atlas levels as raster data in our database. The database is managed by Informix Universal Server v9.2, which is an OR-DBMS. The levels are stored as BLOBs (Binary Large Objects) within the relations. Other attributes include the level ID and image size. The purpose of storing the levels as images, in addition to their spatial structures (see below), is solely for the purpose of quick visualization. That is, the Java applet that serves as the GUI (see Chapter 4.3 for details) can quickly retrieve the entire image corresponding to an atlas level in one shot and display it to the user. The data layers, however, are not stored as raster data anymore.

Spatial Data

Spatial representations of both the Swanson atlas and experimental data have to be stored into the database. Originally, the Swanson atlas consists of a set of 73 electronic drawings in Adobe Illustrator. The curves and lines of the drawings delineate the brain structures, but the spatial structure of many of the constituent spline curves do not fully enclose their respective nuclei in a topologically consistent manner. Some regions lie in areas without complete boundaries, so the exact location of their borders remains unclear. To solve this problem, the Spatial Index Manager was developed to impose a spatial structure onto the atlas drawings, by using a combination of automation and expert user intervention with the GIS geographical topological mapping program (see Shahabi *et al.*, 1999, and Chapter 4.3). This process has converted the atlas drawings into "intelligent templates" in which every point "knows" both the spatial extent and the name of the region that contains it. This "knowledge"—a Spatial Indexing Scheme—is then inherited by any regional data registered against the atlas and thus supports spatial queries anchored by references to particular brain regions, spatial features, or three-dimensional coordinates. In practice, we used the spatial data types defined by the Geodetic datablade v9.14 (an Informix spatial extension) to store atlas spatial data as polygons, arcs, and points.

As for data layers, however, the best spatial representation would be spline curves. Unfortunately, such a spatial data type is not supported by Geodetic; therefore, as a temporary solution, we have them stored as polygons. This representation is, of course, not an optimal one as some spatial relationships between an atlas structure and an experiment (e.g., overlap relation) would not return accurate results. This is because the two corresponding polygons might, say, overlap but the contained spline curves and the structure might not. We could have stored the experiments as a set of points, but this would result in a very low performance for spatial queries.

Spatial Relationships

Once both atlas levels and data layers are spatially stored in the database, all the spatial relationships supported by Geodetic are at our disposal. This includes all the topological relationships discussed above, as well as a limited number of direction and metric relationships. Consequently, one can ask, for example, for all the experiments that had impacts on a specific structure on a specific level of the atlas. This query can be translated to a spatial query that looks for "overlap relationship" between the polygon representing the structure and all the experiments across multiple layers. Now, suppose we georeferenced (or should we say "*neuroreference*") all the neuroinformatics publications with the corresponding coordinates of each structure to which they refer. As a result, we can search for all publications corresponding to a specific structure of the atlas. Note that interacting with a GUI, and not necessarily describing the query in any natural language, can form these queries. Currently, NeuARt's GUI allows the user to select a point, a rectangle, or a circle on a specific atlas level and ask for relevant materials (for now, only experimental data are neuroreferenced).

Coverages

At the first glance, one may be tempted to use the concept of GIS "coverages" to represent atlas "levels;" however, GIS coverages are used to conceptualize a collection of related phenomena—for example, a series of roads or rivers or a specific vegetation type—and there is no tight relationship between two coverages. Basically, there are inherit differences in consistency between GIS coverages when they overlap as opposed to consistency between brain boundaries as we move from level to level through the atlas of the three-dimensional structure of brain. That is, with brain atlases, brain structures exist over many levels. For example, the CA1 field of the hippocampus extends from level 28 to 40 of the Swanson atlas. This is analogous to having a river starting at one coverage and end on another.

On the other hand, it seems more appropriate to apply the concept of coverage to experimental data layers. Consequently, multiple experimental results obtained for an identical level can be considered as multiple coverages superimposed on top of that level. This is identical to representing different coverages for roads and rivers all mapped on top of, say, the California map.

As discussed above, works in GIS and spatial databases on spatial indexing and querying are largely based on the assumption that data are represented in two dimensions via latitude and longitude and can be represented as points, arcs, or polygons. On the other hand, brain regions are "volumes" and have complex shapes (e.g., CA1 field of hippocampus). Extending the works in GIS and spatial databases to support queries across levels on such complex shapes poses several research topics.

Registration and Rectification

In order to register data from other applications onto the atlas, all data have to be registered onto the same atlas. In the neuroanatomy domain, the registration task is more challenging than for GIS. First, there is no standard coordinate system in neuroanatomy corresponding to latitude/longitude in the geographical system. Second, there are no consistent naming standards; the same region in the same species may have different names in different atlases. Finally, the brain varies from one rat to another, not like the single Earth that is not changing rapidly.

To integrate data from different applications into the Swanson atlas, data should be rectified to the atlas and certain registration has to be done. That is, all data need to agree on some unique but shared characteristics to consolidate the information. The registration and rectification methods and theories in GIS, which we discussed above, are applicable here. Obviously, the main problem that arises here is that data source and target site might not agree on a unique frame of reference. Or, even if they do agree, they might not contain the required information for registration. For example, the selected experimental data of a certain query might be from different database and might use a different atlas to reference a brain region than what have been used by the Swanson atlas (Swanson, 1992, 1993).

For neuroanatomy domain, consider the registration of brain-slice images against a standard brain atlas so that one can ask a query to view all the images available about a particular region as seen in the atlas. The challenge is that the brain structure is three dimensional, while a standard brain atlas (e.g., Swanson's atlas) is a series of two-dimensional images. For three-dimensional brain structure projection into two-dimensional images, there is no mature or standard algorithm similar to the geo-map projection algorithms (e.g., azimuth projection, conic projection, cylindrical projection, etc.). To match a two-dimensional image with one of the standard atlas levels, it should be sliced in an identical plane; however, a rat brain is very small, and the odds of slicing a particular brain in the same plane as the atlas sections are very small. The process of superimposing data on the atlas requires a high level of expertise and patience for several reasons. Even so, this cutting and fixing procedures still may cause unpredictable nonlinear distortions of the tissues. Another challenge is the inter-individual variation and time-series variation of the brain structure. These variations make it very difficult to find "ground control points" like in geographical system to execute registration/translation. The approach that USC Brain Project has taken to this problem is to match a given section against many different slices through a three-dimensional brain estimated from the Swanson atlas. Taking advantage of this approach, their tool can be considered as a translation function (either rectification or registration) with two-dimensional rat brain images sliced in different planes as input and the corresponding level(s) and section(s) in the Swanson atlas as output (see Chapter 4.4 for more information).

Another challenge in registration is the uncertainty when dealing with multiple independent translation functions. For example, with neuroscience applications, there exists another standard rat brain atlas, the Paxinos-Watson atlas (Paxinos and Watson, 1986). Not only does this atlas consist of different number of levels, but also each level is based on slicing a different rat brain in a different plane and is partitioned into different sections with different labels. The registration of experimental data on one atlas can be translated to that of another atlas given that a translation function exists. However, the result of this translation and hence the registration might not be exact and certain. That is, a section in the Swanson atlas can correspond to one or more sections of the Paxinos atlas with some probability. The rectification and translation functions need to be extended in order to take into account this uncertainty and provide a method of representing the "spatial" uncertainty to the user. This extension imposes new research challenges that are currently under investigation at USCBP.

4.2.5 Conclusion and Web Resources

We described the primitive data types, operations, and features required by any GIS application. We demonstrated how these features can be supported through a spatial database management system and mentioned several commercial products and the ways they support these features. Subsequently, we explained both similarities and distinctions of a neuroinformatic atlas-based application to typical GIS applications. Consequently, we provided an overview of the GIS features helped in our implementation of NeuARt (see Chapter 4.3) as well as discussing those unique features required by our neuroinformatic atlas-based application that cannot be immediately supported by conventional GIS tools. Specifically, with NeuARt we store atlas layers as both image (raster) types and as collections of spatial objects. The experiments are stored only spatially and data belonging to the same experiments are grouped together as layers similar to the concept of coverage with GIS. Because we utilized a commercial database system with spatial capabilities, most of spatial relationships become readily available to us. Therefore, our Java-based GUI can support spatial queries such as overlap, contain, or point queries by defining a point (by mouse click) or a rectangle or a circle. Finally, neuroreferencing objects such as publications, relevant time-series data, and experimental data remains a challenge due to the three-dimensional and complex structure of the brain.

Below, we provide a list of useful Web sources for GIS and spatial database-related materials.

1. NCR TOR Database: http://www3.ncr.com/product/teradata/object/index.html
2. Informix Geodetic Spatial Datablade: http://www.informix.com/informix/products/options/udo/datablade/dbmodule/informix5.htm
3. Oracle 8 Spatial Cartridge: http://technet.oracle.com/products/oracle8/info/sdods/xsdo7ds.htm
4. Professor Hanan Samet's page at UMD provides spatial Java plug-ins, codes, and index structures: http://www.cs.umd.edu/~brabec/quadtree/index.html
5. Professor Ralph Hartmut Guting's page at Praktische Informatil IV provides a nice overview and survey on spatial models and query languages: http://www.informatik.fernuni-hagen.de/import/pi4/gueting/home.html
6. GIS WWW Resource List: http://www.geo.ed.ac.uk/home/giswww.html
7. ESRI—The GIS Software Leader. This site features free GIS software, online mapping, and GIS training, demos, data, product: http://www.esri.com/

References

American National Standard for Information Systems. (1986). *Database Language SQL* American National Standards Institute, New York.

ARC/INFO (1991). *User Guide, Data Model, Concepts, and Key Terms*. ESRI.

Bekkers, J. (1998). Datamining with GIS, an (im)possibility, in *ESRI International User Conference Proceedings*.

Carter, J. (1989). Defining the Geographical Information System. In *Fundamentals of Geographical Information Systems: A Compendium*. American Society for Photogrammetry and Remote Sensing, pp. 3–8.

Dashti, A. E., Ghandeharizadeh, S., Stone, J., Swanson, L. W., and Thompson, R. H. (1997). Database challenges and solutions in neuroscientific applications. *NeuroImage J.* **5(2)**, 97–115.

Egenhofer, M., and Herring, J. (1990). A mathematical framework for the definition of topological relationships, in *Proceedings of the 4th International Symposium on Spatial Data Handling*, Zurich, pp. 803–813.

Frank, A. U. (1992). Qualitative spatial reasoning about distances and directions in geographic space. *J. Visual Languages Computing*. **3**, 343–371.

Goodchild, M. (1991). Integrating GIS and environmental modeling at global scales. *Proc. GIS/LIS '91*. **1**, 40–48.

Goodchild, M., Steyaert, Louis, and Maidment (1996). *GIS and Environmental Modeling: Progress and Research Issues*. Wiley. New York.

Guting, R. H. (1994). An introduction to spatial database systems. *VLDB J.* [special issue], **3(4)**, 357–399.

Guttman, A. (1984). R-trees: a dynamic index structures for spatial searching. In *Proceedings of ACM-SIGMOD*.

Jones C. B. (1997). *Geographical Information Systems and Computer Cartography*. Addison-Wesley, Reading, MA, p. 30.

Medeiros, C. B., and Pires F. (1994). Databases for GIS. *ACM SIGMOD Record*. **23**, 107–115.

Paxinos, G., and Watson C. (1986). *The Rat Brain in Stereotaxic Coordinates*. 2nd ed. Academic Press, New York.

Pequet, D., and Ci-Xiang, Z. (1992). An algorithm to determine directional relationship between arbitrary shaped polygons in the plane. *J. Pattern Recognition*. **20(1)**, 65–74.

Poage, J. F. (1998). Analyzing spatially enabled health care data using the Dartmouth atlas data viewer, in *ESRI International User Conference Proceedings*.

Shahabi, C. *et al*. (1999). Visualization of spatial neuroanatomical data. In *Proceedings of Visual '99*. Amsterdam, Netherlands, Springer, pp. 201–208.

Swanson, L. W (1993). *Brain Maps: Computer Graphics Files*. Elsevier. Amsterdam.

Swanson, L. W. (1992). *Brain Maps: Structures of the Rat Brain*. Elsevier, Amsterdam.

Thompson, P. M., Schwartz, C., and Toga, A. W. (1996). High-resolution random mesh algorithms for creating a probabilistic 3D surface atlas of the human brain. *NeuroImage* **3**, 19–34.