57 Geographic Information Systems

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57.1 Introduction

Background

Information about our world has been depicted on maps of various forms for many centuries. During the golden age of exploration maps showed critical paths of navigation in the known world, as well as strategic political boundaries and information about settlements and natural resources. Over the past 300 years the art of cartography has been complemented by the development of scientific methods of surveying and related technologies, which have enabled increasingly accurate and complete representation of both physical and cultural features.

Most recently, computer-related advances have led to a revolution in the handling of geographic information.

First of all, raw spatial information can be gathered and processed much more efficiently and quickly, based on technologies such as analytical and digital photogrammetry, Global Positioning System (GPS), and satellite remote sensing.

Second, it has become possible to automate drafting and map production techniques to replace manual drafting procedures.

Third, instead of providing simply a graphical representation through paper maps, it has become possible to model the real world in a much more structured fashion, and to use that spatial model as the basis for comprehensive and timely analyses. Based on this model, it is possible to geographically reference critical data generated by government agencies and private enterprises, and using information modeling and management techniques, to query large amounts of spatially integrated data, and to do so across multiple departments and users, thereby sharing common elements.

The result of this revolution is that there has been a very rapid growth in the production and manipulation of geographic information, to the extent that many organizations can fulfill their production and operational goals only through the use of a geographic information system (GIS).

A geographic information system may be defined as an integrated system designed to collect, manage, and manipulate information in a spatial context. The geographic component, the various technologies involved, and the approach to information modeling set a GIS apart from other types of information systems. A geographic information system provides an abstract model of the real world, stored and maintained in a computerized system of files and databases in such a way as to facilitate recording, management, analysis, and reporting of information. It can be more broadly stated that a geographic information system consists of a set of software, hardware, processes, and organization that integrates the value of spatial data. Various authors provide more detailed definitions of geographic information systems [Antenucci et al., 1991; Dueker, 1987; Parker, 1988].

Early automated mapping systems used interactive computer graphics to generate, display, and edit cartographic elements using computer-aided drafting (CAD) techniques, more or less emulating the manual processes previously used. Over the past decade, more advanced techniques designed to more comprehensively integrate geometric (graphic) elements with associated nongraphic elements (attributes) and designed specifically for map-based and geographic data have resulted in more powerful and flexible implementation of GIS. Continuous mapping, in which a seamless geographic database system replaces map sheets or arbitrary facets earlier used, and the manipulation of geographic information as spatial objects or features are two aspects of most recent geographic information systems that provide users with more intuitive and realistic models of the real world. Also, the integration of vector-based graphics, imagery, and other cell-based information has provided increasingly powerful visualization and analysis capabilities.

Applications

At a broad range of scales, maps have become increasingly important as legal documents that convey land ownership and jurisdictional boundaries, as tools to support decision making (for example, in urban planning), and as a means of visualizing multiple levels of information on political, social, and ecological issues, for example, in thematic mapping of demographic data.

It is estimated that typically 70 to 80% of information maintained by government agencies may be geographically referenced. In addition to directly specifying spatial location on basemap information, such elements as taxpayer identifier, home-owner address, phone numbers, and parcel numbers may be used as the spatial key. Perhaps for this reason, GIS is often seen as the means to promote information sharing and more efficient information management and maintenance, and as a key to providing better and more timely services in a competitive environment. In addition, GIS applications are often both graphics- and database-intensive and provide strong visualization capabilities. The GIS offers the power to process large amounts of various types of information, but also to present results in a powerful graphical medium: The most common standard product of a GIS is for the time being still the printed map, but it is likely to be a cartographic product customized for a specific task or analysis, as opposed to a standard map series product.

In general, a GIS can provide the following information on geographic elements or features: location, characteristics, logical and geometric relationships with other features, and dependencies on other features. This information can generally be used as the basis for tabular reports, standard and custom map output plots, spatial decision support, trend analysis, as well as output to other potential users and analyses. A geographic information system may be accessed from a single PC, a local area network (LAN) of UNIX workstations, or through a virtual, wide area network (WAN) of distributed information.

Standard or common components of a GIS that enable full implementation of such tasks include drafting, data entry, polygon processing and network analysis, spatial querying, and application development tools (macro language, programming libraries).

From earliest times, maps have been used to establish land ownership. One of the first application areas for modern GIS has been in the area of property ownership and records. Within a municipality, the assessor's office or appraisal district is normally responsible for the identification, listing, and appraisal of parcels of real estate and personal property. A GIS provides real benefits to such an office by allowing accurate and complete appraisals, based on access not just to property attributes such as lot size and building square footage, but also to spatial information, such as the comparison of similar properties within a neighborhood. Once the complete map base has been established in digital form and linked to the nongraphic attribute database system, such tasks as property transactions and applications for building permits can be performed efficiently and without a lengthy manual, and often bureaucratic, delay.

Such a parcel-based land information system can provide the basis for a much more sophisticated GIS. For example, within an urban environment, various boundaries define school, library, fire department, sewer and water supply districts, special business zones, and other special tax assessment districts. The allocation of real estate taxes for a given property may be determined by overlaying all of these special districts with property boundaries. Done manually, it is a cumbersome process, and one that makes redistricting — that is, changing the boundaries of any of the constituent districts — a complex process. Polygon processing within a GIS provides the means to perform such an overlay and to determine very quickly how the various tax components apply to one or many properties. The same function can be used to provide answers to discussions regarding proposed changes to these districts, for example, to examine the impact on a city's tax base by annexing an adjacent unincorporated business region. The GIS therefore offers benefits in two areas — first in new capabilities, and second in its ability to produce results in a timely manner: two months of visual inspection and transcription can be replaced by one hour of computer time.

Another key application area is one based on linear networks, such as those defining transportation routes, or an electricity distribution network. In the area of transportation the GIS provides the ability to model individual road elements and intersections and to analyze routes between any two points within an urban street network. Such a network trace can be used in conjunction with emergency services planning to identify the shortest path to a hospital or to examine the average response time to a call to the fire department. By extending the GIS data structure to incorporate one-way streets, turn restrictions in a downtown area, and rush-hour speed statistics, a sophisticated, multipurpose model of the transportation network may be derived. This model can be designed and optimized exclusively for emergency response activities or for planning purposes only — for example, to examine commuting patterns and traffic congestion projections.

The geographic information system provides the ability to completely model utility networks, such as those supplying water, power, and telecommunications to large numbers of consumers. Such a system may operate at a variety of scales, modeling service connections to consumers, service districts, as well as detailed facilities inventories and layouts, such as transformers, valves, conduits, and schematic diagrams.

The GIS then becomes a key element at many levels: in customer support (to respond to service failure), in maintenance and daily operations (to identify work requirements and assess inventories), and in planning (to respond to projected needs). It provides the link between many information systems, including engineering, planning, and customer billing, which can increase overall performance and operational efficiency.

These simple examples identify the key elements of a geographic information system: a base model that identifies spatial features and spatial relationships, a set of descriptors that can be used to discriminate and identify individual elements, and a set of functional processes and tools that operate against all information components. This structure is also shown in Fig. 57.1. Typical bases for application areas are shown in Fig. 57.2.

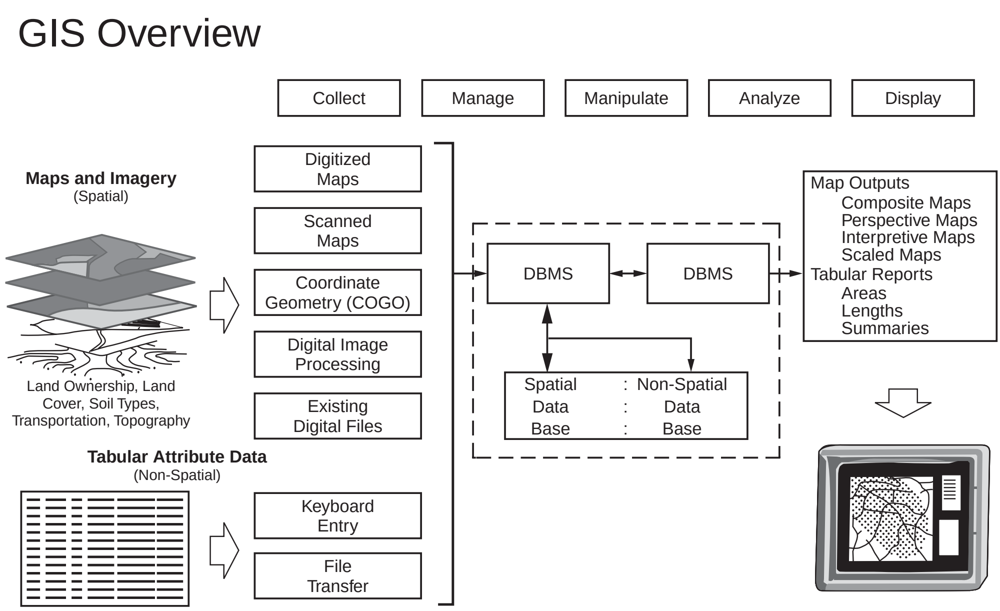


FIGURE 57.1 Overview of a geographic information system (GIS).

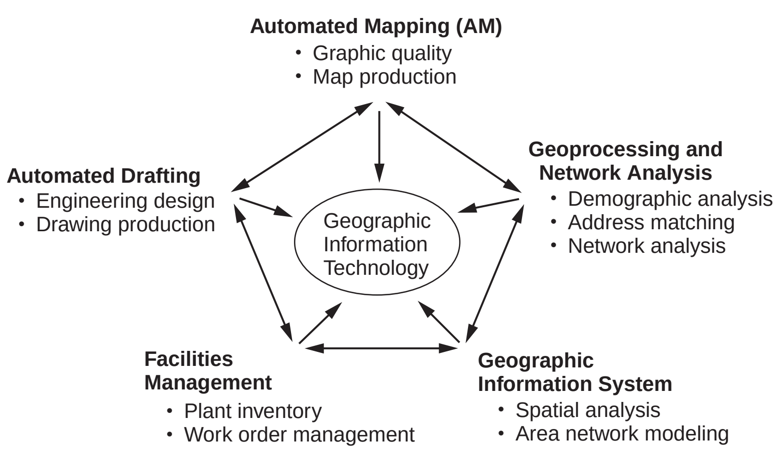


FIGURE 57.2 Application areas based on geographic information technology. (*Source:* Antenucci et al. 1991. *Geographic Information Systems: A Guide to the Technology.* Van Nostrand Reinhold, New York.)

Key	Type	Usage
absolute location	X, Y(,Z) coordinates	survey monuments
relative location	distance, bearing	property boundaries
parcel identifier	alphanumeric	land ownership transactions
street address	alphanumeric	ownership
street segment ID	alphanumeric	traffic engineering
manhole ID	alphanumeric	water/wastewater utilities
zip code	numeric	demographics
telephone number	numeric	pizza delivery

FIGURE 57.3 Keys to geographic information.

57.2 Geographic Information Components

Geography provides a reference for a very large amount of information commonly stored and maintained in information systems. In many cases this reference or key is not necessarily absolute position or a set of geographic coordinates, but an indirect key to location such as street address, parcel or property identifier, phone number, or taxpayer number. One of the distinguishing properties of a geographic information system is the ability to tie such keys to a common geographic base, such as a basemap containing streets, property information, and so on. Some common keys for geographic information are identified in Fig. 57.3.

In fact, the geographic information system is often seen as a focal point for various types of graphical and nongraphical data collections.

Initially, we can look at these components separately.

Geometry (Graphics)

As previously discussed, GIS has generally evolved from computer graphics systems that allowed the graphical representation conventionally depicted on map products to be modeled as layers that can be displayed, edited, and otherwise manipulated by means of specialized software. Today's CAD systems still provide the same type of structure. In such a GIS, graphical elements forming a logical grouping or association are stored on distinct layers or even in separate files. A final graphical display or map output is formed by switching on or off the appropriate layers of information and assigning to each layer a predefined cartographic representation designed for the scale of map or specific application. The symbology or line style to be used is traditionally stored with the layer definition, although it is also normally possible to define special representations for specific graphical elements.

Spatial location is typically stored directly or indirectly within the graphical component of a geographic information system. In earlier systems a complete GIS project stretching across many map sheet boundaries would be stored still in the form of distinct tiles or facets, each representing a drawing with its original spatial extent. Absolute spatial location in a reference coordinate system, such as a state plane coordinate system, would be obtained by interpreting for each drawing part a local transformation (a two-dimensional conformal transformation typically) applied to drawing coordinates. A librarian system would allow such transformations to be applied transparently to the human operator or indeed to applications interested only in absolute spatial location.

More recent systems provide a more seamless continuous map base, where geometric components are stored in a single reference coordinate system that models the real-world representation of geographic features. Any trimming or splitting of the database to map sheet boundaries or other artificial tiling systems is more typically completely hidden from anyone but the project manager or system administrator, as depicted in Fig. 57.4.

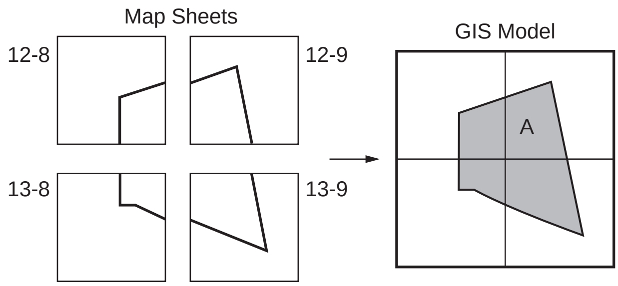


FIGURE 57.4 Map sheets in a GIS. A diagram showing how map sheets stored in separate data files are referenced within a geographic information system in order to model a continuous spatial extent. Polygon A can be accessed as a single geographic feature, regardless of where individual segments of boundary lines are stored.

Attribute Type	Typical Size / Storage Requirements	GIS Feature Example
short integer	2 bytes	land use class
long integer	4 bytes	land value
floating point real	4 bytes	area
double precision real	8 bytes	centroid coordinate
fixed length text	32 bytes	street name
variable length text	80 bytes per line	property description
bulk	30 kbytes for compressed 256x256	scanned image of building
date	6 bytes	land purchase date

FIGURE 57.5 Typical attribute types.

Attributes (Nongraphics)

As already mentioned, the critical distinguishing property of a GIS lies in its ability to relate various types of information within a spatial context. Such a context is provided directly through absolute or relative location or through nongraphic characteristics, also referred to as attributes. Such attributes may act as direct or indirect keys that allow the analysis of otherwise unrelated sets of information.

We should also distinguish between internally defined attributes or keys that typically maintain the link between the geometry component and the nongraphic database system. This key is often the weakest link within a GIS, especially if geometry and attributes are stored and maintained in distinct file or database systems.

Attribute information is typically held in a relational database management system. GIS applications typically allow the retrieval of nongraphic and geographic information in a linked fashion. For example, it is possible to point to a specific location in a graphical map display, to select and identify an individual spatial feature, and to retrieve or update attribute information relating to this feature. Conversely, it is possible to select spatial elements on the basis of attribute matching and to display the selection in a graphical form such as a thematic map. A variety of attribute types are commonly used, as shown in Fig. 57.5.

Vector

The tremendous growth in comprehensive geographic information systems over the past decade reflects the implementation of vector-based GIS software systems that can handle a variety of point, line, and

Vector Element	Parameters	Typical Size / Storage Requirements	GIS Feature Example
node / point	(x,y)	16 bytes (double precision floating point)	centroid of parcel
line	(x_1,y_1), (x_2,y_2)	32 bytes	service connection between house and utility main
line string / polyline	(x_1,y_1), ... , (x_n,y_n)	20 points require 320 bytes	stream
circular arc / circle	(x_0,y_0), radius,θ_{start},θ_{end}	40 bytes per arc	curved portions of roadway
spline	B_0,B_1,B_2,B_3 coefficients for each segment	20 segments require 640 bytes	contour line
complex / composite line	combinations of the above	combinations of the above	oddly-shaped parcel boundary
polygon / surface	(x_1,y_1), ..., (x_n,y_n)	4-sided polygon requires 64 bytes	boundary of municipal service district
Triangulated Irregular Network (TIN) element	(x_1,y_1,y_1),(x_2,y_2,z_2), (x_3,y_3,z_3)	500 triangles require 3600 bytes	digital terrain model (DTM)

FIGURE 57.6 Vector data components (2-D, 2.5-D applications).

polygon geometries. Based on these structures, as in Fig. 57.6, all geometric information previously depicted on hard copy maps could be modeled, stored, and manipulated. Although in earlier systems it was common to hold a third dimension (the *Z* coordinate or elevation) only as a nongraphic attribute of the geometric entity, geometric structures in a modern GIS typically hold all three coordinates for each primitive component. The following geometric structures, also shown in Fig. 57.5, are normally available:

1. Point or node elements, each containing *X*, *Y* or *X*, *Y*, *Z* coordinates.
2. Line elements, containing or referencing beginning and end nodes, along with a set of intermediate points, sometimes referred to as shape points. In addition to straight-line connections between shape points, other primitive line types may be modeled, including circular arcs defined by three successive points or parametrically (including complete circles) or B-spline connections between all points in a single entity. Such flexibility in line primitives allows more efficient modeling of certain types of spatial features: for example, the outline of a building would be defined by digitizing corner points (vertices) only; a street centerline may be defined using the appropriate parametric geometry, whereas a digitized contour line may be held for cartographic purposes with a B-spline connection.
3. Polygons, surface or area primitives, are closed polyline elements used to represent enclosed areas of the earth's surface, such as property boundaries, lakes, and so on. A GIS typically allows for the formation of polygon boundaries based on one or more line primitives and also maintains special information about "islands" or "holes" within the enclosed area. Such structures allow the appropriate modeling of, for example, a pond on an island on a large inland lake. As this example might indicate, more important than the geometric primitives themselves is the overall data model, including vector-based topology between elements.

Raster

Some of the earliest computer-based GISs were based on grid-cell information. Before the definition of more complex structures and the availability of computing power to support their processing, the simplest way to perform a spatial analysis between multiple layers of information was to subdivide each layer into a grid of small cells, with an associated numeric cell value which denoted a class or set value representing the characteristic of that location. By performing simple Boolean operations between the grids representing each characteristic, useful results could be obtained.

At the same time that raster-based GIS products have been incorporating more vector graphics and database structures, vector-based products have been providing support for raster information. It is now possible to display scanned engineering drawings, maps, digital orthophoto products, and other raster-based imagery, coregistered with vector map information in a common geographic reference system. This can be seen as part of a broader trend to incorporate both vector- and raster-based structures in a single software system where spatial analyses may be performed using the most appropriate technique. For example, cartographic modeling based on raster data allows the simple analysis of such properties as adjacency and proximity, but processing requirements increase according to the spatial precision or resolution required. Future software is likely to allow rule-based conversion of information (from raster to vector, and vector to raster) prior to manipulation, dependent on the specific output requirements.

Topology

The power of a geographic information system lies not only in the data that are held within the system, but also in the data model that provides the fundamental structure or framework for the data. A basic component of a vector-based GIS is a set of topologic structures that allows the appropriate modeling of points, lines, and polygons.

Start- and end-node points of linear elements are often stored as distinct structures, thereby allowing the analysis of adjacent or connected entities through such logical connections, as opposed to simply a graphical operation. For example, two lines representing road segments that cross each other may intersect at an intersection point stored explicitly as an intersection, as opposed to an overpass.

Arc-node topology allows the formation of geometric structures that model elements such as a street centerline that contains straight-line segments, circular, and spiral curves. In addition, aspects such as tangency conditions between connected line elements are also considered a part of the topology. During geometric processing, such as interactive editing, all topology properties would normally be retained or at least restored after processing.

Polygonal geometry stores its own set of topology, including the element of closure between beginning and end points of an enclosing boundary. References to islands or holes within the boundary are also maintained as part of the topology for that feature.

Software tools to create and maintain polygon- and linear-based topology are common required elements of a GIS.

In a polygon coverage — such as a continuous coverage of soils, land use, or similar — it is often of value to store such area classifications with line-polygon topology that allows the analysis of shared boundaries. In such a structure, linear elements that form boundaries between adjacent polygons are referenced by both polygons. Such a structure also allows common geometry to be stored only once, allowing efficient storage and maintenance of related information. In a modern GIS it is possible for single geometric elements to reference not just two areas within a single classification (for example, adjacent areas of soil), but any real-world elements that refer to the same geometry — for example, a property boundary that also forms part of the boundary of municipal jurisdictions (tax districts, school districts) as well as forming a right-of-way boundary.

Another important topologic structure is the composite or complex feature, which allows the grouping of logically related graphical and nongraphic elements. This extends the power of a GIS beyond simple relationships between a single spatial element and one set of attributes to a more sophisticated modeling

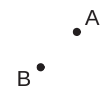
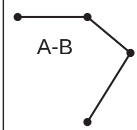
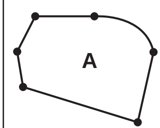
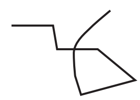
Topologic Type	Description	Properties / Operations	Graphical Representation
Node / point	discrete x,y(,z) identifying unique feature	position / proximity	
Line	straight-line (two points), arcs / circles, splines	continuity / connectivity nodes at all intersections and at endpoints	
Polygon / surface	series of connected line segments	areal closure / adjacency	
Spaghetti	sequence of connected points, with no topologic checking	length (line segments may cross/intersect each other)	

FIGURE 57.7 Node-line-polygon topology.

of real-world elements. Through the use of composite features, a logical spatial feature may be defined — such as a school district composed of a school district boundary, a set of school facilities (classrooms, playing fields, administrative offices), school bus routes, and residential catchment areas — that permits more sophisticated modeling of spatial elements.

More sophisticated topologic structures involve those that allow the formation of a single seamless geographic base structure, where graphic or geometric components cross tile or district boundaries that are stored in distinct files or database tables, but referenced. In such systems users may access large or small spatial features.

Topologic structures such as those identified in Fig. 57.7 form one of the most critical aspects of a GIS since they determine how efficiently certain operations or analyses can be performed. (Network analysis depends on connectivity between line elements; polygon analysis requires handling of closed polylines, islands, and so on.)

57.3 Modeling Geographic Information

In this section various methods of modeling spatial information are described. The method chosen has broad implications on the scope and application of GIS.

Layer-Based Approaches

The traditional method of classifying information in a geographic information system derived from the ability to graphically distinguish various layers or levels of data, also affected by the practical limitations of available computing capacity (for example, limits of 256 layers or 32 colors in a palette). Compared to previous means of producing hard copy maps, though, these restrictions did not prevent reasonable modeling of geographic data. Rather, it allowed the storage, maintenance, and manipulation of many more levels of information than previously possible through manual drafting or overlay means.

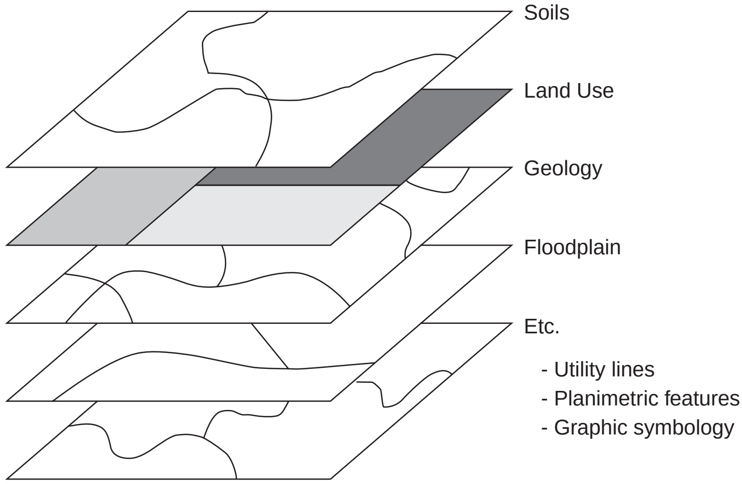


FIGURE 57.8 Layers in a geographic information system. (*Source:* ESRI. 1992. *ARC/INFO: GIS Today and Tomorrow.* ESRI, Redlands, CA.)

In a layer-based approach, the ability to distinguish different types of information relies on a common definition and usage of layers, the schema or data dictionary. Such a schema, agreed upon by all potential users, defines that graphic primitives (lines, arcs, point symbols, text labels) common to a well-defined set of spatial features are stored in separate and distinct layers. The layer specifications determine how information once collected can be used, since in a graphics system the layer may be the only level at which logical data may be segregated. For example, text labels annotating parcel numbers may be stored in layer 25, and parcel boundaries themselves (the graphical primitives) in layer 24: By separating text and pure graphics, it is then possible to display either graphics, text, or both. In practice, separate layers of information may in fact reside in separate files on disk, physically as well as logically distinct. The layer-based model is closely analogous to logical map overlays or use of color separates as used in map production. Figure 57.8 shows typical graphical layers in a GIS.

Relational Approaches

As a first step in the evolution from a purely graphical system, it was recognized that links to additional nongraphic attributes in a GIS would radically increase the utility and power of such an information system. Although early GISs provided an ability to graphically model and depict cartographic information (much in the same way that paper maps had done previously), such systems became extremely cumbersome and limiting when trying to really apply the power of computers to selective retrieval and analysis of spatial information. This resulted in the development and introduction during the 1980s of a GIS with two distinct components: the graphical database or file system, and an associated nongraphic database system. Early systems used proprietary database structures to store and reference nongraphic information, but the more rapid growth and acceptance of GIS in the past few years has come with the use of standard commercial relational database management systems (RDBMS). Spatial information systems using such an approach are also referred to as *geo-relational* or *all-relational* GIS, the latter term denoting that at least some of the geographic or graphic components are also stored in a relational model.

The simplest relational model used in GIS consists of a graphics-based component that carries with each geometric primitive (point, line, or polygon) a unique internal identifier or tag, which is the means to associate the geometry with additional nongraphic information defining the characteristics of the spatial feature. The geometry identifier is therefore the common key upon which the power of the relational GIS depends. Although the use of such identifiers is often hidden from the casual user, its role is critical: the means that a GIS software system uses to establish and maintain this vital link between graphics and nongraphics determines the practical potential of the system.

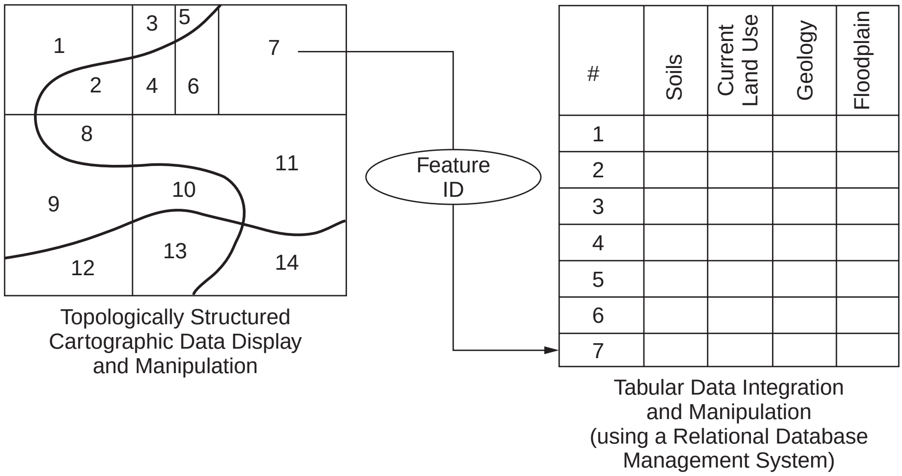


FIGURE 57.9 The geo-relational model. (*Source:* ESRI. 1992. *ARC/INFO: GIS Today and Tomorrow.* ESRI, Redlands, CA.)

Once linked using the relational model, commonly used and widely understood techniques and tools may be applied in all areas of spatial data management, including data collection, update of nongraphic information, extraction, and reporting. Apart from the key link between geometry (graphics) and primary attribute (nongraphics) tables, it becomes a simple matter to extend the model through additional tables and keys. Common elements in such tables may be used as additional keys through table joins to incorporate the spatial context to a variety of nongraphic information. For example, property information including property addresses can be joined with a table containing address and telephone number in order to provide direct retrieval of phone numbers based on property and location. The relational model can also be used to associate sets of geographic features with common characteristics, such as those properties lying in a specific school district, thereby extending the spatial and logical models as appropriate.

In addition, certain relational terminology can be applied directly in the spatial domain: for example, a polygon overlay can be viewed simply as a "spatial join."

With the acceptance of standards within the RDBMS industry and with extensions of commercial products to provide transparent access and manipulation of information in a broadly distributed network of computing platforms, the geo-relational model has fit well for those GIS projects seeking to play a key role in a multidepartmental or enterprise-wide information technology environment. In such situations the GIS project manager is often happy to take advantage of these standard commercial products and in turn is able to concentrate on issues of data management specific to the geographic nature of the information.

As already mentioned, it is also possible to model geometry and topology using relational database technology. In such GIS, sometimes referred to as all-relational, such information as start and end nodes, pointers between line entities, and polygon elements may be stored in the form of relational tables. A purely relational approach sometimes adds tremendous computing overhead for simple operations in a GIS (for example, geometric editing of polygonal areas) and may require additional levels of information to be stored in a hybrid fashion to improve performance. Figure 57.9 shows the geo-relational model.

Object-Oriented Approaches

Object-oriented approaches in data modeling were applied early on in CAD products, in such areas as construction and manufacturing. Such a model allowed an architect to apply object-oriented rules to form walls with certain properties and optional or mandatory components (for example, windows and doors). Once a certain type of (standard) window had been modeled, it could be introduced and reused wherever appropriate.

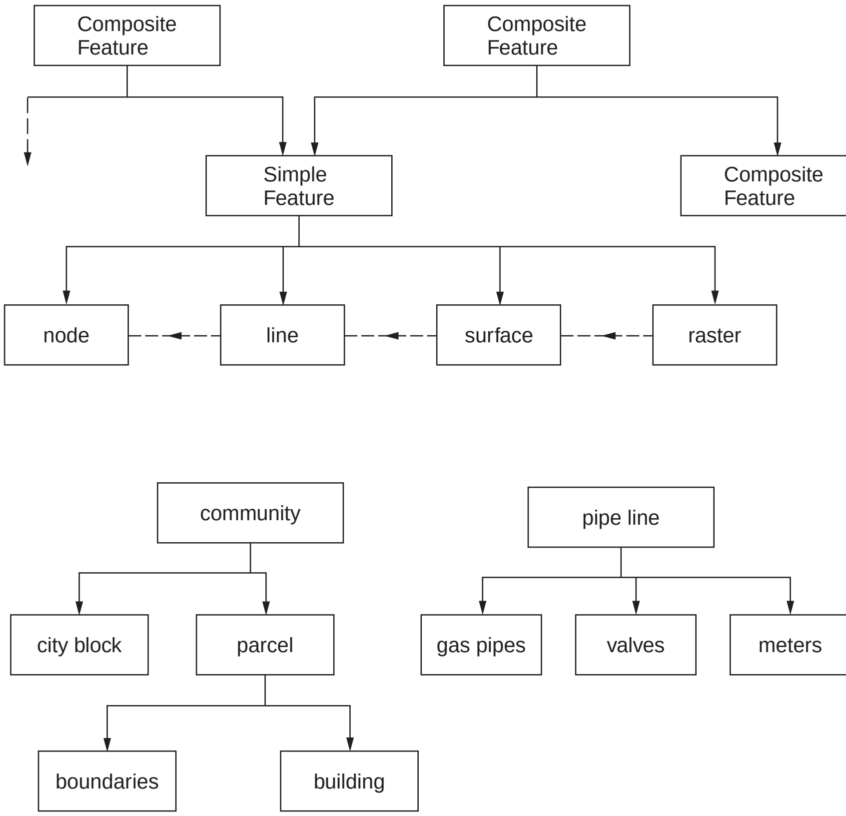


FIGURE 57.10 A GIS data model.

Over the past few years, object-oriented techniques have been applied to GISs in at least two major areas: (1) spatial data modeling, and (2) spatial analysis or programming tools.

In any geographic information system the database and related software attempt to create an abstract model of the real world (as in Fig. 57.10) containing spatially dispersed information. The closer this abstract comes to modeling true characteristics of the physical and human-made world, the more powerful can be the application of computing power to interpret and provide decision support based on the geographic information. We discussed in a previous section the various components of spatial information: An object-oriented approach to spatial data modeling allows all related components to be encapsulated in a single object or feature definition, along with rules that govern how the object may be manipulated or how components may be related or dependent on components of other objects. The terms *feature oriented* or *feature based* are also used to denote software systems in which the modeled entity is intended to closely reflect the real-world element or object. In such an example a land-ownership record may be treated as a single spatial object or feature containing one or more boundary lines with surface (polygon) topology, additional nongraphic characteristics, and logical associations. Relationships based on common boundaries (logical adjacency) or common ownership may be accommodated. The object-oriented paradigm allows for the modeling of sophisticated groupings of geographic and logically related elements, such as a "census tract" composed of a collection of "parcel" objects, or a "gas distribution network" composed of various subelements such as "pipes" and "valves." Once such elements are defined, the data dictionary contains not just a list of element classes, but the rule base for their use and application. This permits, at least in theory, the population of highly structured geographic data sets in which many real-world relationships and constraints are retained.

Many GIS software products now claim to be object oriented or feature oriented. To a certain degree, such GISs have introduced levels of object-oriented user interfaces or modeling techniques, which may mask a layer-based or fully relational model that the system uses internally. For the time being at least, there are few GIS products that claim to be fully object oriented in both data modeling and data storage: This situation will probably change as object-oriented database management systems (OODBMS) become more widespread.

Extended Relational Model

Although the object-oriented paradigm carries many advantages — especially in areas of accurately modeling real-world phenomena or features and ability to develop or customize geo-related applications based on reusable blocks of code — the relational model carries with it many positive aspects when considering implementation of GIS projects. These relate to existing (or legacy) information systems that are to be somehow incorporated into or integrated with geographic information, the flexibility and increasing power of commercial RDBMS in handling large amounts of distributed data, and the use of industry-standard products and techniques in accessing and manipulating such information. The use of *structured query language* (SQL) and products such as Oracle and Informix has become widespread in large and small organizations, to the extent that large commercial companies may choose to standardize on the use of a specific RDBMS product. Commercial database products are constantly being extended to address such areas as multimedia (additional and custom data types), the object-component paradigm, as well as specific requirements for spatial data. In this way the growth of OODBMS is being countered by the major RDBMS vendors, many of whom are in the best position to package and offer the best of familiar (relational) technology with additional features addressing these more specialized requirements.

The geographic information system places a considerable burden on data management, from the aspects of both modeling real geographic features and the various types of spatially distributed data. A GIS is often seen as providing the common interface or natural reference system to which attribute, vector, raster, video, sound, and other multimedia data are to be attached. Such an information system was beyond the scope of purely relational database management technology a few years ago, but now several RDBMS provide the facilities to develop such support in an extended relational model.

Security and Information Sharing in a GIS

Early GIS projects were restricted to single users or single departments where data were gathered and processed by at most a small group of individuals. In such implementations little attention was paid to the role of making information secure or of handling multiple user transactions.

However, in many organizations today, the GIS project implementation carries a significant weight as a means of integrating or linking multiple agencies and departments based on (spatial) elements of common interest or value. The general problems of data duplication, inconsistencies, and inaccuracy associated with uncontrolled access to all information within the database system can no longer be ignored. In fact, the introduction of multiuser security to spatially related data elements allows the full benefit of a GIS.

First of all, the layers or classes of information stored in a GIS are typically of interest to more than one user or group of users. However, one user or department is responsible for the creation and maintenance of a single class of data. The goal must be to eliminate duplication both of spatial geometry and of attribute information.

As an example, in a large municipal environment, the private land ownership unit — the "parcel" — may have many fields associated with it. The same parcel is referenced by many departments, but each department views the fields differently. Most importantly, only one department — for example, the department of public works — is empowered with the creation of new property boundaries. This department must work closely with the appraisal district to allow the assignment of a unique property identifier and street address, to allow further information to be applied correctly. Figure 57.11 shows additional examples.

Data inconsistencies can be minimized by the use of controlled procedures and standards for all information handling. However, a database system must also provide controls by allowing tables and basic elements to be accessed in a read-only mode, for read-write, or to be completely restricted. When dealing with geographic data, the example above shows that although one user may require write access to geometric components of a spatial object, other users require write access to specific attribute fields

CLASS / LAYER attributes	Users		
	Public Works / Engineering	Assessor	Planning
PARCEL			
boundary	write	read	read
identifier	read	write	read
street address	write	read	read
land value	-	write	read
improvement value	-	write	read
total value	-	write	read
date of last sale	-	write	read
owner name	-	write	read
owner address	-	write	read
zoning	read	read	write
tax district	read	read	write
STREET			
centerline	write	read	read
right-of-way	write	read	read
name	write	read	read
TAX DISTRICT			
boundary	-	write	read
name	-	write	read
taxes	-	write	read

FIGURE 57.11 Security in a multiuser GIS. This diagram shows read/write access privileges to classes of information for three different groups of users (departments) in a multidepartmental GIS.

for which they are responsible. For example, the assessor is responsible for assigning taxable values to individual properties, whereas the planner may be responsible for the zoning for specific properties. A good GIS provides a unified database management system that permits such combinations for geometric and attribute components. In addition, many GISs that rely on the relational model support and make use of security characteristics of the underlying relational database management system. In this situation individual tables and table records may be locked for read-only access or restricted completely.

In many GISs access to spatial data is managed in conjunction with a checkout procedure, whereby a group of information corresponding to the area of interest (a map sheet for example) is made available to one user only for updating and restricted to read-only access for all others. A transaction-oriented information system often takes this to a more elemental level, in which any database transaction locks out a small set of data immediately prior to the transaction. An AM/FM system often aims for this level of security, in which changes to facilities status and geometric elements are critical. This issue of concurrency — where in theory no two users may access the same data elements for update at the same time — can be achieved only with a sophisticated management of graphic and attribute elements.

57.4 Building and Maintaining a GIS

This section discusses the primary issues in building a geographic information system.

Reference Coordinate Systems

A geographic information system requires the definition and application of a reference coordinate system. The choice of a reference system is typically based on accuracy requirements, geographic scope of the

Type	Extent	Source Data
Latitute/Longitude (geographic coordinates)	global	field geodetic / world maps
Universal Transverse Mercator (UTM)	worldwide zones, each 6 degrees of latitude wids	national / transcontinental
US State Plane Coordinate System	State / portion of State	state / country maps and documents
Project-specific	Projectwide (engineering / construction)	airport / builting site

FIGURE 57.12 Reference systems for source data.

proposed GIS, and the predominantly used reference system for source data, as shown by examples in Fig. 57.12.

For example, engineering and property maps within a small municipality are typically referenced to a local grid based on state plane coordinates. An information system that is to be applied for work at national or international levels may require the use of a true geographic reference system (latitude, longitude) to provide true seamlessness and consistency across the entire area of interest. It should be noted that the reference coordinates for the GIS database storage often differ from a local working coordinate system. For example, data entry may derive from large-scale maps referenced to state plane coordinates. In this situation the digitizing and data validation operations take place in state plane, but, once complete, all information is transformed and stored in the project's primary coordinate system. Information may later be extracted and presented in a variety of local coordinate systems, without corrupting the primary data storage.

Consideration of Scale

In a traditional mapping system, consideration of precision of data is closely tied to final map scale. In theory, a GIS requires a much broader view of both data accuracy and precision, because it is open to data at large range of scales and accuracies. Unfortunately, most GISs do not in practice allow the maintenance of data quality and accuracy information. Furthermore, many applications of GISs involve the merging and integration of spatial data of differing resolutions and accuracy. The results of such operations are often used in decision support without regard to their statistical reliability. For example, the results of overlaying parcel boundary information derived from 1″ to 50′ scale property maps and soil classification boundaries derived from 1″ to 1000′ orthophotos may be used to determine the taxable value of farm properties.

It is therefore critical that the overall design of a GIS takes into account the accuracy requirements as a function of the application intent.

Data Sources

A variety of data sources are available for input to a GIS, as depicted in Figs. 57.13 and 57.14. They can be classified most simply as follows:

- Local maps and related documents
- Existing local information systems
- Commercially available information
- Government sources

GIS implementation is often the driving force behind conversion of existing maps and other documents and records.

Source	Source Scale	Accuracy
Field Survey, total station		.02 m
Field Survey, GPS Carrier Phase Differential		.05 m
Photogrammetry, large scale	1:4,000	0.3 m
Digitized Engineering Map	1:600	0.5 m
Photogrammetry, medium scale	1:16,000	1.5 m
Photogrammetry, small-scale	1:40,000	3 m
Field Survey, GPS Pseudo-range Differential		5 m
Digitized USGS Quad sheet	1:24,000	15 m
Bureau of the Census TIGER files	1:24,000	20 m
Remote Sensing, SPOT panchromatic, rigorous model		20 m
Field Survey, GPS pseudo-range single receiver		50 m
Remote Sensing, Landsat TM panchromatic, rigorous model		60 m
USGS Digital Line Graph	1:2 million	100 m

FIGURE 57.13 Typical data sources. This table indicates typical source materials and methods of spatial data collection, with resultant accuracies.

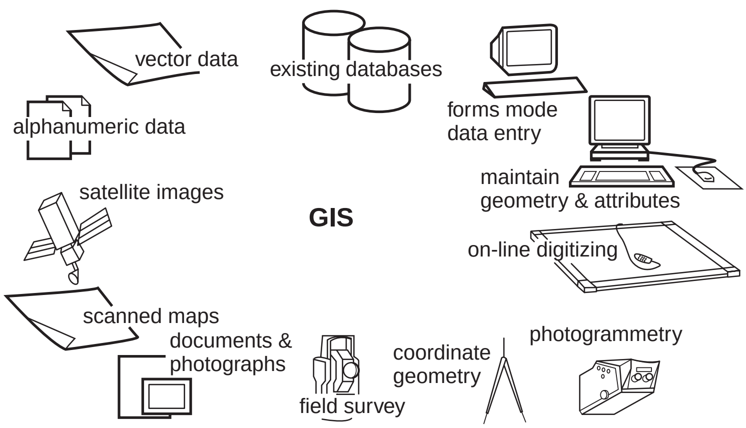


FIGURE 57.14 Data sources.

Data Entry and Processing

The data entry process may be reviewed in terms of:

- Interactive or semiautomated conversion of existing map documents
- Interactive update of attribute information through use of forms
- Batch loading of digital files

Interactive digitizing of existing maps has been superseded in part by a semiautomated process in which documents are scanned, displayed as a registered backdrop to vector data, and converted as necessary. Software that provides line-following and recognition capabilities, augmented by text recognition and a rules-based means to associate printed text labels as descriptors for adjacent graphic elements, may be applied successfully to conversion projects involving a large number of consistent map documents.

In addition, a key component to GIS database implementation is the linking of existing information systems. This is achieved as part of the overall database schema definition by identifying the key that provides the link between the core GIS and the existing data records. For example, the digitizing of parcel maps may include the interactive input of parcel identifier. Once a spatial feature containing the parcel number has been created, existing databases also containing the parcel number can be incorporated and accessed through the GIS. Alternatively, the parcel number may be used as a key to load additional attributes through a batch import process or as a guide to interactive form entry.

Structure/Topology

The data entry process normally includes facilities to check overall consistency and validity of data. The level to which these facilities operate is determined by the source data and the means of entry.

For digitizing operations and import of digital files representing vector geometry, it is critical that the input geometry defines a record that is consistent with both nongraphic descriptors and other graphic elements. For processing of vector line data, operations that determine intersections with adjacent geometry, extend lines to provide polygon closure, or eliminate overshoots are typically applied. Since these operations alter geometric components, they must be used with care and often use a correction tolerance determined by the ultimate accuracy requirements. This operation is often referred to as "building and cleaning," or "feature assembly." In addition, the process of "conflation" allows the merging of line data from disparate sources to minimize data storage and permit more consistent assignment of descriptive attributes. For example, street centerlines derived from small-scale TIGER data may be conflated to highway alignment data derived directly from the local engineering department. This process actually "moves" inaccurate TIGER geometry to the more accurate engineering data, but then allows the use of the other TIGER data, such as street names and address ranges. Figure 57.15 identifies database and geometry linkages used to build a GIS.

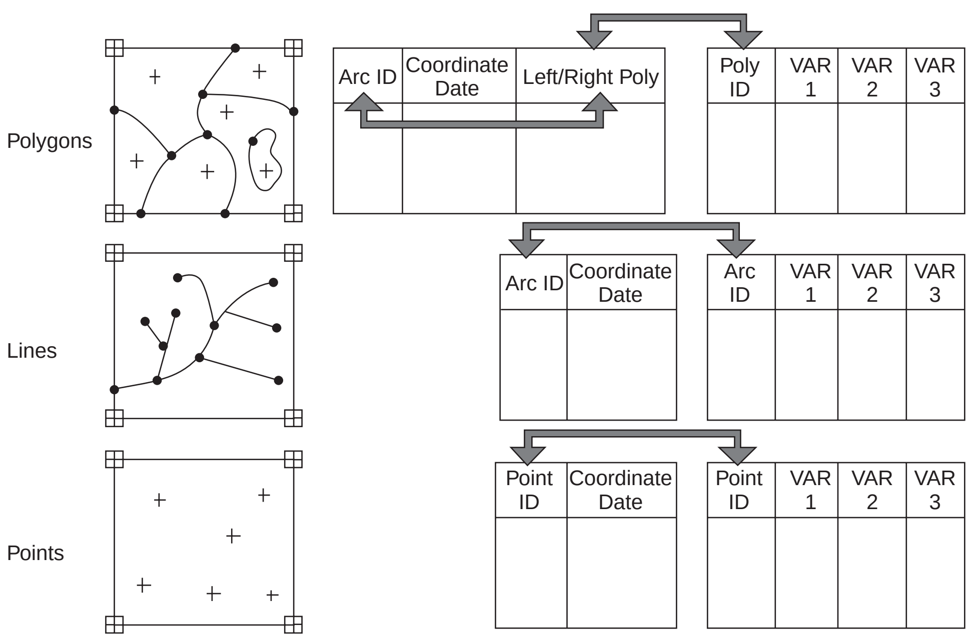


FIGURE 57.15 Database and geometry links. (*Source:* ESRI. 1992. *ARC/INFO: GIS Today and Tomorrow.* ESRI, Redlands, CA.)

Maintenance Operations

Once the primary spatial database has been created, it is important that maintenance operations may be applied without corrupting either geometric or attribute components. This is the most critical aspect to GIS editing as compared to a graphics-driven CAD system, in which the graphical elements and representation are most critical. For this reason, maintenance operations are most often performed on a primitive spatial object with both graphic and attribute components accessible. Nongraphic updates and edits may take place at a graphics workstation or at a simple alphanumeric screen, where operators update form entries.

57.5 Spatial Analysis

Beyond the implementation of GIS purely for mapping and map production, its key value lies in the ability to perform analysis based on spatial location and relationships between spatial elements. Such spatial analysis is augmented by the incorporation of external database records and application models.

Database Operations

We will now consider three groups of database operations associated with spatial information systems.

The first is simple querying and identification of individual geographic features and all related information. These may be nongraphic queries that return information based on nongraphic characteristics or graphical queries that incorporate a spatial extent to limit the extent of a querying process. Address matching, in which a nongraphic query provides street locations and/or property identification, is a fundamental operation in linking address as a reliable key between geographic and nongraphic information. Conversely, a graphical selection (for example, by pointing to a display) can be used to return a set of nongraphic information or a report. Querying and extraction operations are described later in this chapter.

The second group of operations are based on pure spatial analysis, based on geometric properties of individual elements. These apply to point, line, and polygon data as seen in Fig. 57.16. These include the generation of polygonal buffers around points, lines, or polygons and the overlay of multiple layers of polygonal information to provide a "spatial join" to be used in further processing and analysis. Properties such as proximity, distance, overlapping, and containment are included in this group.

The third group of operations rely on point, line, and polygon topology to provide the basis for analysis. Such properties as adjacency, connectivity, and composed of are included in this group. Linear network analysis provides the basis for shortest path calculations in transportation, distribution, and collection applications. Figure 57.16 identifies some commonly used spatial database operations.

Of course, the typical GIS application may use many database operations, spatial and nonspatial, to provide the desired answer. As an example, the simple question "How many people live within 1/2 mile of the proposed light rail line?" is typically answered by proceeding through the following steps, each one a distinct database operation:

- Identify the light rail line (spatial).
- Create a 1/2-mile corridor/buffer based on the location of the rail line.
- Overlay the rail corridor against census block information.
- Transfer demographic information from census blocks to results of overlay.
- Produce summary statistics for population from the overlay.

Coupling to External Analyses/Applications

As previously discussed, the geographic information provides a powerful, common context for many different applications. In many cases the geographic key provides a much more significant means of interpretation or analysis than a simple numeric or textual key (for example, location versus street

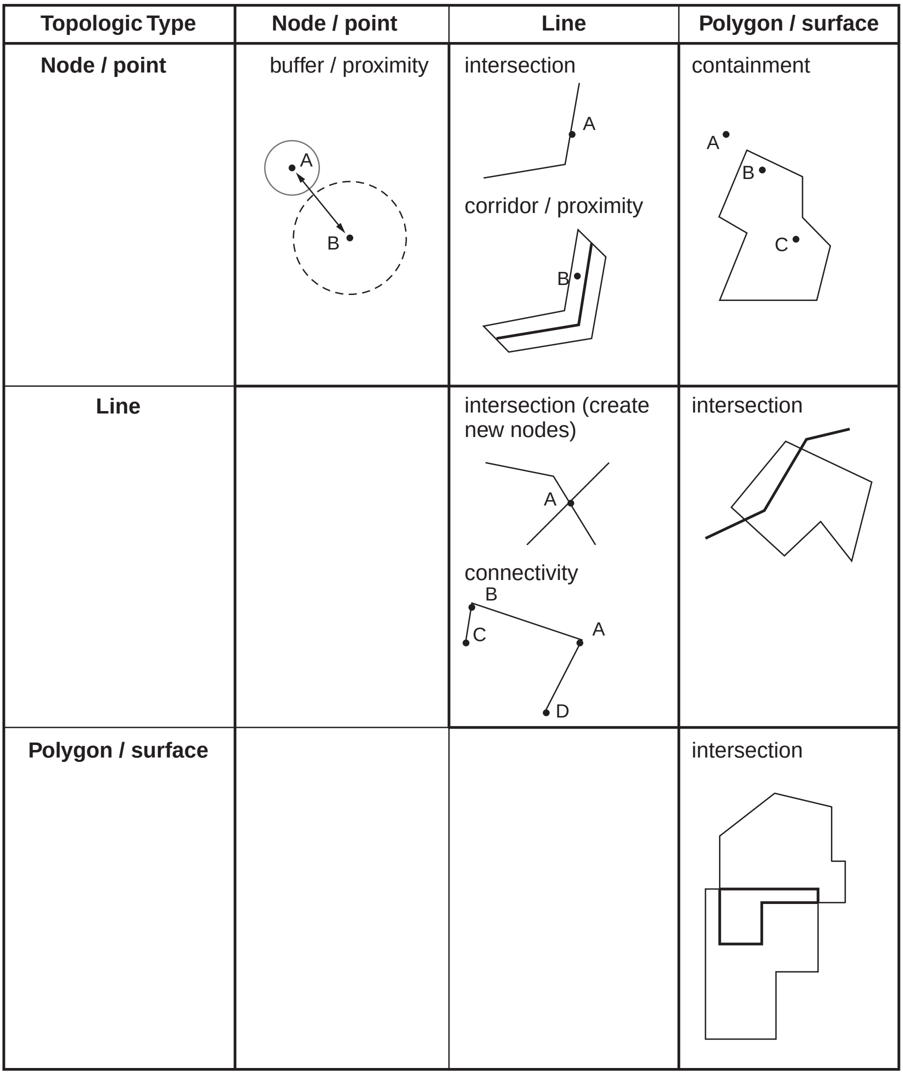


FIGURE 57.16 Spatial database operations. Typical operations involving two input geometries (row and column).

address). The structure of a GIS lends itself to linking with additional software and procedures that can be considered "external" applications. Examples are:

- Groundwater pollution models
- Statistical analysis
- Traffic engineering analyses

Data Interchange Standards and Formats

In practice, the exchange of data between geographic information systems has been inefficient and incomplete, except in situations where both systems share a common implementation. Two departments within a single organization, for example, may exchange information in a format recognized only by those departments. Such a practice results in the widespread exchange of information in commercially proprietary formats, such as those of Arc/Info coverage files or Intergraph design files. When geographic data are to be transferred to other agencies or to be imported from other sources, it is common to resort to one of several widely used standards.

Digital Exchange Format (DXF), introduced by Autodesk in conjunction with its AutoCAD software product, is probably the most widely used means to exchange geographic data between CAD systems, desktop mapping systems, and even more sophisticated GISs. It is most effective as a means of encoding graphic elements but has severe limitations in the areas of handling topology, attributes, and more complex data structures. This means that the exchange of any DXF file must be accompanied by additional information describing the layering convention, symbology rules, and coordinate references. Such metadata is not normally incorporated in the DXF. Because spatial information must be resolved into simple graphic components and separate but related attribute information, both the source and target systems must provide additional utilities to ensure that all data is interpreted correctly.

Other formats, such as DLG (Digital Line Graph) and TIGER (Topologically Integrated Geographic Encoding and Referencing System), have been devised and introduced by federal government agencies as a means to deliver digital geographic data to the public, other agencies, and commercial users. They go beyond standards such as DXF in that they are designed to handle line and polygon topology, common data layer classifications, and real-world coordinate systems (as opposed to a graphics-based standard that often refers to "drawing units").

More recently, the Spatial Data Transfer Standard (SDTS) has been designed as a means to model, encode, and transfer geographic information. The SDTS goes far beyond previous standards, in that it provides a comprehensive means (1) to define spatial phenomena and spatial objects used to represent phenomena, and (2) to model spatial features in a hierarchical fashion. The exchanged data include not only the raw geographic components, but also the definition of rules that associate the geometric, attribute and topologic elements, and any other metadata that further define the information. First practical implementations of SDTS, involving only a subset of the standard, have been developed for topologically structured vector data. This is referred to as the *vector profile*. Subsequent implementations or profiles will support raster- or grid-based data, such as imagery, digital orthophotos, and terrain models. The SDTS was approved as a Federal Information Processing Standard, Publication 173 (FIPS 173), in July 1992. Federal agencies such as the U.S. Geological Survey and the Bureau of the Census are now required to supply spatial information in an SDTS profile.

The use of structured query language (SQL) and other facilities associated with the relational database management system also provides the means to exchange spatially related data.

57.6 Information Extraction

The GIS has evolved over the past decade from a mainframe-based software system with distributed graphic terminals, through workstation clusters focusing high-performance graphics processors in a departmental fashion, to a more distributed organizational component. The corporate or enterprise-wide information system now typically includes a component dedicated to geographic data handling. Access to and extraction of information from a GIS takes place in various ways, depending on the nature and extent of the data required.

Displays and Reporting

As mentioned in the introduction to this chapter, the most standard product derived from a GIS remains a map. This map may be part of a standard map series, replacing the map product previously derived using manual drafting techniques, but increasingly common is a variety of custom maps and graphical displays that highlight the flexibility of a GIS in presentation of data.

For the typical GIS user the graphical display on a workstation or PC is the typical medium for interaction with the data. Layers or classes of information may be selected from a menu or list, for display at a variety of scales, along with attribute information as textual annotation or as a menu form. Specific layers and attribute information may be switched on or off based on scale of display or other criteria. Multiple windows may be used as a means to guide the user through large amounts of spatial information:

A where_clause may have Boolean expressions of the form:

```
EXPR  [        is        ] CONDITION
               is not
null            EXPR
```

A CONDITION is:

```
[OPERATOR]  [EXPR]
in (EXPR{, EXPR} )
```

Examples of OPERATOR are:

```
Comparision Operator:
               =, !=, >, >=, <, <=, range (between)
Pattern-matching Operators:
               like, match, not match
Spatial Operators:
               overlap, contain, near, left_of, adjacent to,
```

Examples of queries in a GIS:

```
select house where house.address = “5623 South Avalon” and house.zip_code = “43211”

select street where street.address_number range (5600,5700)

select house where house near (select river where river.name = “Colorado”)

select house where house overlap (select soil_area where soil_area.type = “clay”)
```

FIGURE 57.17 Query language. The where clause forms part of a query language that is used to retrieve database records satisfying certain conditions specified. The where clause consists of Boolean expressions that can be nested or used in combination, and that evaluate to TRUE or FALSE.

For example, an overview window showing index maps or major features may be used as a constant reference to a larger-scale display in the current window.

In addition to information displays in standard cartographic forms (point symbols, line styles, and area fills and patterns), a thematic display of one class of information may be generated. Such displays rely on nongraphic characteristics such as “property value” or “soil type” or “road classification” to determine the cartographic representation. Thematic maps allow the efficient visualization of information. Also possible are more advanced representations, sometimes referred to as *cartograms*, such as the ability to size symbols based on attribute characteristics (for example, “tree height” or “drain size”) or the ability to generate pie charts based on attributes (for example, “registered voters: Democrats” and “registered voters: Republicans”).

Increasingly, the output from a GIS is not just a graphical product but a simple report or statistic. Spatial analysis can provide a set of information regarding a subset of spatial information. Thus, a letter to be sent to all property owners within a 1/2-mile buffer of a proposed industrial development may be the final product, based on spatial analysis and reporting.

Spatial Query Languages

In the geo-relational model a critical component in the GIS is the link between nongraphic and graphic elements. In such a model there are normally extensive sets of tools to allow access to, processing of, and retrieval of attribute information stored in tables. The *structured query language* (SQL) standard provides a common syntax for identifying and extracting specific table entries for further processing. Relational database management systems, such as Oracle and Ingres, are used broadly in conjunction with GIS components.

The critical nature of this link lies in the fact that once a database key is corrupted, the real value of the geographic information is lost and is difficult or impossible to recover. The second difficulty in the geo-relational model lies in the fact that the spatial component requires a distinct management system.

Commercial GIS products have attempted to introduce a geographic query language or spatial query language that incorporates many SQL components but is augmented by specific spatial operators. More recently, the ANSI SQL Committee has proposed spatial extensions to a query language. Commercial RDBMS vendors are also active in this area.

57.7 Applications

In this section we examine further some typical roles of geographic information systems.

Basemap and Infrastructure in Government

In an introductory example we discussed the use of GIS for handling land records and property ownership. In fact, this is but one role for geographic information management in local government. Typically, a set of basemap information — including property boundaries, highways and rights of way, public buildings, and other major transportation and drainage features — form the basis for a multidepartmental information system. During implementation and extension through multiple departments, additional attributes are added to these layers, and additional layers are created. In a sense the GIS allows the modeling in a rigorous, structured fashion of the annotated basemap that previously would have been found in individual agencies of municipal government.

In many situations a GIS is the sole means for providing required services, including meeting local, state, and federal legislative requirements. In Florida, for example, each community is required to submit a master plan that includes land-use zoning, transportation, and residential and commercial zoning plans. In addition, environmental impact regulations require the consideration of multiple levels of information (transportation, residences, zoning, water and wastewater, soils, vegetation, habitats) in producing reports and recommendations: A multilevel GIS is often the only means to meet planning requirements in a timely fashion.

Currently, federal legislation requires all communities to implement a management and control system for storm water runoff. For large cities this requires major work not only in informing property owners and enforcing compliance with regulations, but also in compiling all of the background data required for analysis. This includes terrain-modeling data, as well as complete watershed and drainage network information. However, the timetable for compliance with these regulations requires a computer-based system of information for analysis and prediction.

In general, we can review the capabilities and advantages of a GIS as lying in the areas of:

- *Operation*. Being able to provide response and service requests effectively.
- *Planning*. Being able to anticipate and plan responses, for example, to emergencies.
- *Information sharing*. Allowing multiple agencies to share cost of data collection and maintenance.
- *Decision support*. Providing qualified recommendations to management for review and action.

Facilities Management

For utility companies, such as those dealing with very extensive networks and facilities for the distribution of electricity and gas, a geographic information system is typically an integral part of a program aimed at improving operational efficiency, improvements in planning and engineering work, and higher service quality. These goals can be met by implementation of a GIS with powerful characteristics, which results in the ability to store and model spatial information at many levels: an upper management level that provides summaries updated on a regular basis; an intermediate level that provides all centralized management information to be used on a daily basis for business control and decision making; and the basic, "on-line" information level used for operational transactions.

A typical implementation is developed around a core facilities database that contains the following:

- Background cartographic, such as highway maps as political boundaries
- Operational facilities, including all information on installations forming the distribution network and data on maintenance, breakdowns, and other incidents
- Network of facilities under construction, showing facilities not yet in service
- Planned network, containing planned facilities

The system provides the following capabilities based on this core database:

- Maintenance of all necessary network diagrams and worksheets
- Maintenance of all alphanumeric (descriptive) information regarding facilities and operations
- Alphanumeric queries on all networks and facilities
- Production of all necessary reports, drawings, plans, and maps

Development Tools (Means to Customize/Build New Applications)

There is always a compromise between implementing a GIS based on standard commercial products, while attempting to maintain the ability to customize a system to accommodate specific and changing requirements over time. There are several levels at which GIS products may offer such capabilities. We may consider these in terms of profiles of the various end-users:

- *The casual user*, with little programming experience
- *The GIS specialist*, with detailed knowledge of spatial data handling and operations
- *The GIS programmer*, with experience in spatial data handling and programming expertise

For the casual user of a GIS standard tools are typically available that allow repetitive or predictable operations to be stored as a macro or command file, which may then be invoked with a single command or menu operation. As commercial GIS products begin to reflect simplistic and intuitive graphical user interfaces — such as those consistent with Windows on a PC platform or X-Windows on a UNIX workstation — facilities such as the ability to "learn" a sequence of menu selections or command-line arguments are those that most simply allow some limited customizing.

The GIS specialist who understands the full capabilities of a specific software product always uses this knowledge to extend its operational use through various combinations of basic functions and operations. For example, a well-known commercial GIS product now offers roughly 800 operations through command-line options and a much smaller number of graphical user interface components such as menus, submenus, and pull-down selection lists. The more advanced macro language permits the extension of simplistic sequences of operations to include flow control, user interaction, and menu components.

The GIS programmer uses knowledge of all programming components — including subroutine libraries supplied with the GIS, user interface libraries, and other programming tools — to develop a high-level application that either can be integrated with standard GIS operations or can completely replace the menus and options made available to the end-users of the information system. In this case the MIS department or an independent software developer may provide a completely customized interface for multiple departments within a large organization. For high levels of integration with other information systems, such programming is typically required. For example, GIS programming tools used in conjunction with high-level tools provided by Oracle relational database management system can provide the optimized functions and operational performance required.

57.8 Summary

This chapter has described the way in which map data are now often being incorporated directly into a computerized information system. A geographic information system typically attempts to link geometric, spatial information with related nongraphic or attribute data from one or many sources, thereby providing a direct spatial context for many databases. Since a large proportion of nongraphic data held by government agencies and certain types of private companies relate to geographic location and context, the introduction of GIS technology has been driven by such organizations in an attempt to make more efficient use of information and to allow more effective information management. GIS provides a more complete model of the real world than can simple (carto)graphic representations or tabular records or reports. In areas of local government and in private utility industries, the GIS approach is synonymous with information sharing, systems integration, and reengineering, in the name of providing more effective service in a competitive environment.

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