Geographic Information System—Basic Concept and Application

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1 Introduction

The *geographic(al) information system* (GIS) consists of two distinct disciplines, namely, *geography* and *information system*. Geography is the science which involves a combination of physical and cultural disciplines, which are used to describe, explain, and help us to understand our environment and our relationship with it. It is the science of space and place that brings the earth's physical and human dimensions together in the integrated study of people, places, and environments. Information system most often refers to a system containing electronic records, which involves input of source documents, recording on electronic media, and output of records, along with related documentation and any indexes.

The GIS is a computer-based information system used to digitally represent and analyse the geospatial data or geographic data. Geospatial means the distribution of something in a geographic sense; it refers to entities that can be located by geographic coordinate system. 'Every object present on the earth can be georeferenced', is the fundamental key of associating any database to GIS. Here, term 'database' is a collection of information about things and their relationship with each other, and 'georeferencing' (or spatial referencing) refers to the location of a feature or coverage in space defined by the geographic coordinate referencing system.

The GIS is a particular form of information system applied to geographical data. A system is a group of connected entities and activities which interact for a common purpose. For example, a car is a system in which all the components operate together to provide transportation. Thus, an information system is a set of processes, executed on raw data to produce information which is useful in decision making. The information system is a chain of steps that leads from observation and collection of data through analysis.

A GIS uses geographically referenced data ([geo]spatial data) as well as non-spatial (attribute or descriptive) data and includes operations which support spatial analysis. In GIS, the common purpose is decision making for managing use of land, resources, transportation, retailing, oceans, or any spatially distributed entities. In this context, GIS can be seen as a system of hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modelling, and display of spatially referenced data for solving complex planning and management problems.

Although many other computer programs can use spatial data (e.g., computer aided design (CAD) and statistics packages), GIS includes the additional ability to perform spatial analysis/operations. Earlier we had paper maps, which were very colourful, but not modifiable. Then, the computer revolution took place, where the maps were digitised and stored in digital format. These were just geometric entities (line, circle, polygon, or point) and did not provide any information about what that entity implied in geographical terms. These digital files were easily modifiable and could be reproduced quickly, but could not be used for any analysis purpose. Then came the GIS, which made these entities intelligent. It attached a value (attribute) to these entities, with what it actually means in geographical terms.

A GIS can be thought as a set of interrelated subsystems, which consists of data processing subsystem, data analysis subsystem, information use subsystem, management subsystem, and communication subsystem.

2 Functions of GIS

The questions that a GIS is required to answer are mainly as follows:

What is at...?
This is a location-based question, which seeks to find out what exists at a particular location. A location can be described in many ways, using, for instance, name of place, post code, or geographic reference such as longitude/latitude or X/Y coordinates.

Where is it...?
The second question is a conditional one. Instead of identifying what exists at a given location, one may wish to find location(s) where certain conditions are satisfied (e.g., an English medium school for girls within 1 km from the residence or from our place of work).

What has changed...?
This question identifies geographic occurrence or trends that have changed, or in the process of changing. It might involve both the first two questions and seeks to find the differences or changes over time (e.g., change in land-cover during last 10 years in a city).

What spatial patters exist...?
This is a relational question that analyses the spatial relationship between objects of geographic features. For example, we may wish to determine whether habitats mostly grow near river streams.

What if...?
This is a model-based question, for example, computing and displaying an optimum path, finding a suitable land, locating a risky area against disasters, and the like. Information on geography as well as other related topics (and also on specific models) is necessary to answer such types of questions.

3 Spatial, thematic and temporal dimensions of geographic data

Data are the observations made from real-world experiences, organized and processed in order to make them meaningful, and convert into information. All geographic data have three modes or dimensions, such as spatial, thematic, and temporal. Let us consider an example, 'a fire station at 10 Mahatma Gandhi Road started with a capacity of 5 fire engines and 15 staff members'.

The *spatial dimension* includes location-based information, in the aforementioned example; the fire station is located at '10 Mahatma Gandhi Road'. It describes the position of a place over the earth, though it is in a textual form. However, in GIS, it is necessary to represent this location in a geographically referenced data layer (map). With respect to GIS, spatial data is considered as location-based data of the earth, which has been represented graphically on a digital map.

The *thematic dimension* describes the characteristics of spatial data, which is also referred to as attributes or non-spatial data. The above example describes some characteristics of the fire station, such as the number of fire engines and staff members.

The *temporal dimension* provides a record of when the data were collected. Temporal data sometimes became very crucial. In this example, it is not essential to know when the data was collected, rather if someone says, ‘temperature at 22°N 88°E was 35°C’, it is essential to know when it was collected to complete the data, because it lacks the temporal dimension. In this example, the complete form should be ‘temperature at 22°N 88°E was 35°C on 15 May 2006 at 12 noon’, which contains all the three dimensions—spatial (location), attribute (temperature), and temporal (date/time).

4 Spatial data model

The real world is too complex for our immediate and direct understanding, so we create ‘models’ or abstractions of reality that are intended to have some similarity with selected aspects of the real world. A spatial database is a collection of spatially referenced data that act as a model of reality.

There are three main types of data models used for spatial data: *conceptual*, *logical*, and *object-oriented*. Understanding the type of data model by which a particular dataset is created and stored is important, since the type of functions or transformations that can be performed on the data is dependent on how it is represented and organized.

Conceptual data models

Conceptual data model organizes principles that translate the real world into functional descriptions of how phenomena are represented and related to one another. According to this concept spatial features may be discrete (objects) or continuous (fields). Objects are with discrete boundaries represented by geometric features. Discrete features are those that do not exist between observations, those that form separate entities, and are individually distinguishable. Roads, buildings, water bodies, etc. are examples of discrete features. Fields are continuous phenomena such as elevation, temperature, and soil chemistry; they exist everywhere (every point has an elevation or temperature); they are not discrete entities. Continuous features exist spatially between observations.

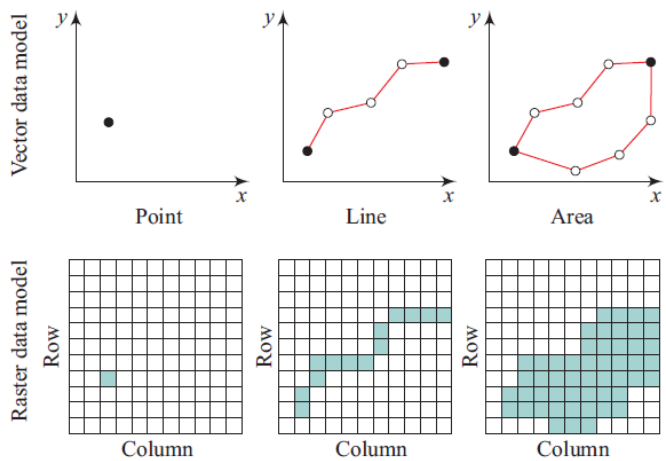
Maps have used symbols to represent real-world features (or spatial entities). Examination of a map reveals three basic symbol types, which are points, lines, and areas. Points have no dimensions, lines have a single dimension, areas are two-dimensional (2D), and volumes have three dimensions (3D). Points are used to represent features that are too small to be represented as areas. An example is a post-box. Lines are used to represent features that are linear in nature, for example, roads or pipelines. Areas are represented by a closed set of lines and are used to define features such as playgrounds, ponds, buildings, or administrative areas. Volumes are used to represent 3D earth features (in a 3D map), for example, 3D buildings or any other 3D features. One can notice that points, lines, areas, and volumes are discrete features-they do not exist everywhere (at every point on the earth). Therefore, these are considered as 'objects' in conceptual data model.

Apart from the kinds of data mentioned in the preceding paragraph, surfaces are another kind of spatial data, which represent continuous data like elevation, temperature, rainfall, population density, etc. They have existence at every point on the earth. Surfaces can also be represented in 3D mode, such as topography, but they can represent only continuous data and not discrete entities like a 3D building. Surfaces are considered as 'fields' in conceptual data model. In GIS, continuous surfaces such as terrain surface, meteorological observations (rainfall, temperature, pressure, etc.), population density, and so on are required to be modelled. Topographic surface models are also referred to as digital terrain model (DTM). A DTM is a digital representation of terrain features including elevation, slope, aspect, drainage, and other terrain attributes.

High-end GIS software can integrate surface models into spatial analysis. Land erosion susceptibility, viewshed analysis, flooding prediction, mining potential, site selection, and countless other projects are greatly enhanced by surface modelling. Other layers of information such as land cover and hydrography can be overlaid onto topographic surfaces for a 3D view of the landscape. Satellite imagery or digital aerial photos can also be overlaid onto surface models to obtain a more realistic view of an area.

Logical data models

Logical data model provides the explicit forms of representation, which the conceptual model can take. According to this concept geographic features can be represented in two different formats: raster and vector (refer following figure).



Representation of objects (point, line, area) as vector and raster

Raster data are represented as an array of grid cells. Vector data are represented as points, lines, polygons, and volumes. Raster data, according to concept, are suitable to represent fields or surfaces. On the other hand, vectors are suitable to represent discrete entities or objects. However, exceptions also do exist.

There are advantages and disadvantages of using a raster or vector data model to represent reality. Raster data represents a graphic object as a pattern of cells, whereas vector data represents the object as points or a set of lines drawn between specific points. Let us consider a line drawn diagonally on a piece of paper. A raster file represents this image by subdividing the paper into a matrix of small squares—similar to a sheet of graph paper—called cells. Each cell is assigned a position in the data file and given a value based on the colour at that position. Raster works best for surface modelling and for applications where distinct features are not important. Terrain elevations can be recorded in a raster format and used to construct digital surface models.

A vector representation of the same diagonal line records the position of the line by just recording the coordinates of its starting and ending points. Each point is expressed as two or three numbers (depending on whether the representation is 2D or 3D, often referred to as *x,y* or *x,y,z* coordinates). The vector line is formed and displayed by joining the measured points. Each entity in a vector file appears as an individual data object. It is easy to record information about an object or to compute characteristics such as its exact length or area. It is much harder to derive this kind of information from a raster file because they contain little (and sometimes no) discrete geometric information.

Object-oriented Data Model

The object-oriented data model uses object-class concept to organize spatial data. One of the impacts of the GIS was to introduce a whole new way of looking at spatial data. Although cartography has been operating digitally for years before GIS appeared on the scene, the emphasis was solely on producing maps. The biggest change, which GIS introduces, is to store geographical features as distinct objects. So a road is stored as an object with certain attributes. These attributes include its name, its type (i.e., a road), its quality (i.e., a highway), and a sequence of coordinates that represent the path, which the road follows across the landscape. In this object-oriented approach, each geographic object belongs to some class of object. Object models are usually described in terms of classes of objects and the relationship between them. For instance, roads and highways can be defined as two classes (as they are maintained by two separate agencies), but there is a relationship between them (as both are used for transportation).

Classification of objects depends on what attempt to support with our GIS. Understanding our needs helps us to decide about classification. For example, a roadway engineer in a municipality might consider all roads as one class. The classification is based on a number of common characteristics such as roads have lanes, they are covered with a surface (e.g., asphalt), and the surface is in a particular state of repair. All highways, streets, and lanes falling within the municipality is classed as 'road'. Perhaps the municipality is not responsible for maintaining highways within its boundaries, and therefore the characteristics of surface type and condition for highways are no longer of interest. In this case, we might identify two classes, 'road' and 'highway', each with different characteristics or attributes.

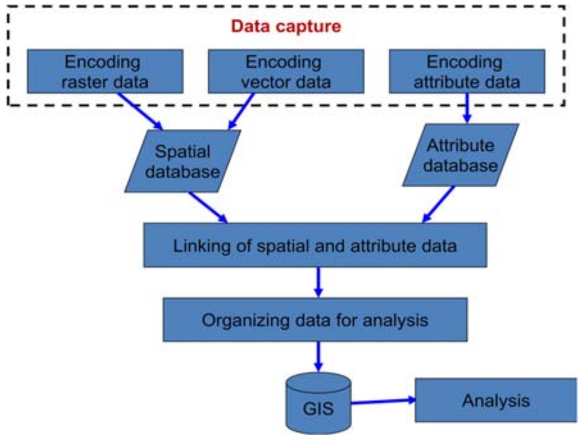
A transit engineer responsible for all bus routes in the municipality can use both roads and highways for route planning. The two classes can be combined into a higher-order class, perhaps called thoroughfare. This classification allows both the roadway and transit engineers to perform their tasks. This last example is a case where a higher-order class is composed of reasonably similar classes; vehicles can travel along roads and highways. It is also possible to create higher-order classes where the underlying classes (subclasses) are different in nature.

An airport, for instance, is a collection of runways for aeroplanes, buildings for people, and parking for vehicles. Common characteristics about airports are that they have a name, a code, regular hours of operation, and so on. In organizing data, we can classify geographic features with similar characteristics (roads, highways), group classes that are similar (roads + highways = thoroughfares), and group dissimilar classes (runways + buildings + parking = airport). An approach to organizing data is to identify the following:

- What we (or our organization) wish to do with our GIS.
- What data we require to support our GIS objectives.
- The characteristics of that data (attributes) and adjust our classification if required.
- The spatial data model best suited to each of our data classes and adjust our classification if required.

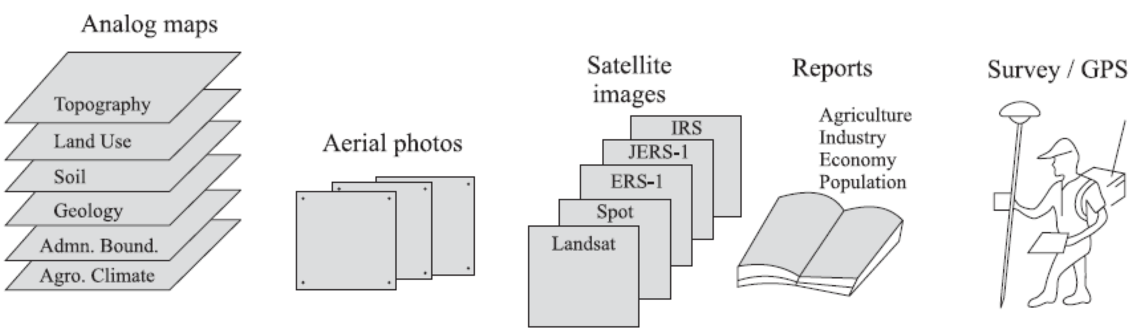
5 Process of GIS

This section describes the process of creation of GIS. The creation of GIS is neither always a linear process nor a single process, which can be applied for all cases. However, this section includes the common methodologies adopted for the creation process of a GIS, starting from data capture to organizing data for spatial analysis (refer following figure). Since data analysis and presentation is a versatile process and requires detail discussion, it will be discussed separately in Section 6.



Process of GIS

The GIS technology is based on digital information, for which there are a number of data collection methods involved. Data capture is the operation of encoding (entering) data for inclusion into a digital database. The creation of accurate databases is a very important part of GIS. Data collection and the maintenance of databases remain the most expensive and time consuming aspect of setting up a major GIS facility. This typically costs 60–80 per cent of the overall costs of a GIS project. The power of a GIS comes from the ability to relate different information in a spatial context and to reach a conclusion about this relationship. Most of the information we have about our world contains a location reference, placing that information at some point on the globe. A GIS, which can use information from many different sources in many different forms, can help with various analyses. The primary requirement for the source data involves knowledge of the locations for the variables. The data sources for data acquisitions should be carefully selected for specific purposes. The data sources for GIS can be categorized as shown in following figure.



Major data sources for GIS

The entire process of encoding, correcting, and transforming has to be done for creating different layers from the existing data sources. Simultaneously, attribute data are attached or linked to these layers. This approach allows integration of existing attribute databases with spatial objects by the allocation of a unique identifier (ID) to each entity in the GIS. The ID of spatial data should match with the corresponding ID of attribute record. Once we join both types of data (spatial and attribute) using any GIS software, our GIS is now ready.

Most GIS software organize spatial data in a thematic approach that categorizes data in vertical arrangement of layers. The definition of layers is fully dependent on the organization's requirements. For example, typical layers used in natural resource management agencies include forest cover, soil classification, elevation, road network (access), ecological areas, hydrology, etc. Others use other kind of data layers. The clear identification of the requirements for any GIS project is necessary before any data input procedures, and/or layer definitions, should occur. It is mandatory that GIS users fully understand their needs before undertaking a GIS project in order to effective analysis and obtain best output of a GIS.

The GIS may be used in various ways soon after its creation. The main uses of GIS are data analysis and presentation of spatial data. The GIS data can be analysed and presented in various ways. Any management problem can be solved or decision be taken, depending on the results of analysis.

6 Geospatial Analysis

Spatial or geospatial analysis is the process of modelling, examining, and interpreting model results. A model is a representation of reality in a numeric format capable of being displayed and manipulated. We can create a model that helps answer the question we have posed by combining data and applying some analytic rules. Spatial analysis is useful for evaluating suitability and capability, for estimating and predicting, and for interpreting and understanding. The most important function of GIS is to enable the analysis of the geospatial data and their attributes for decision support.

Geospatial analysis is undertaken to answer questions about the real world, including the present situation of specific areas and features, the change in situation, the trends, the evaluation of capability, or the possibility of using overlay technique and/or modelling, and prediction. Therefore, geospatial analysis ranges from simple arithmetic and logical operation to complicated model analysis.

Results of geographic analysis can be communicated with the help of maps, reports, charts, etc. The organization of database into map layers is not simply for reasons of organizational clarity; rather, it is to provide rapid access to data elements required for geographic analysis. The objective of analysis is to transform data into useful information to satisfy the requirements or objectives of decision makers at all levels in terms of detail. An important use of the analysis is the possibility of predicting events in another location or at another time.

The GIS has the capability of carrying out any number of analyses related to any discipline-oriented problems. The techniques of spatial data analysis have been developed in a diverse range of disciplines that include plant and animal ecology, geostatistics, landscape ecology, geography, applied statistics, and many others. However, common geospatial analysis techniques include:

- Database query
- Geospatial measurement
- Overlay operations
- Network analysis
- Surface analysis
- Geostatistics
- Geovisualization

It is not within the scope of this lecture to discuss on them in detail. A brief introduction is being given.

Database query

Selective display and retrieval of information from a database are among the fundamental requirements of GIS. The ability to selectively retrieve information from GIS is an important facility. Database query just asks to find already stored information. Both raster and vector can be queried.

Geospatial measurement

Sometimes, merely looking at a map does not solve problems; it is necessary to measure data. Measurement is also a type of query; however, it does not select any object from the GIS database, instead it gives some statistical/mathematical/geometrical result by measuring the map or resulting a map. Three types of geospatial measurements are mainly very popular—measurement of density, measurement of distance, and measurement of neighbourhood.

Overlay operations

The hallmark of GIS is overlay operations. The capability to overlay multiple data layers in a vertical fashion is the most required and common technique in geographic data processing. Vector- and raster-based softwares differ considerably in their approach to overlay.

Raster-based software is oriented towards arithmetic overlay operations, e.g., the addition, subtraction, division, and multiplication of data layers. The nature of raster data model usually provides a more flexible and efficient overlay capability. The raster data model affords a strong numerically modelling (quantitative analysis) capability. Most sophisticated spatial modelling is undertaken within the raster domain.

In vector-based systems, overlay is achieved by the creation of a new theme (data layer) from two or more existing themes. The result of a vector is a new theme that contains attributes of the original input data layers. In this way, selected queries of the original layer can then be undertaken, e.g., soils and forest cover, to determine where specific situations occur, e.g., deciduous forest cover where drainage is poor. Till date, the primary analysis technique used in GIS applications, vector and raster, is the overlay of selected data layers.

Network analysis

The movement of people, the transportation, and distribution of goods and services (such as street network, telephone cable network, pipelines, drainage, etc.), the delivery of resources and energy, and the communication of information all occur through definable network systems. Network connectivity is based on geometric coincidence, hence the name geometric network. A geometric network has a corresponding logical network. The geometric network is the actual set of feature classes that make up the network. The logical network is the representation of the network connectivity. Each element in the logical network is associated with a feature in the geometric network.

Network analysis is a range of techniques employed by engineers and planners to study the properties of networks, including connectivity, capacity, and rates of flow. The 'cost' in a network analysis is a frequently used term, which refers to distance or travel time. Basic forms of network analysis simply extract information from a network. More complex analysis processes information in the network model to derive new information. One example of this is the classic shortest path between two points. The vector model is more suited to network analysis than the raster model.

Surface analysis

Surfaces can be well-represented by a raster digital elevation model (DEM); however, vector can also represent surfaces very efficiently. Analysis of surface is very important in GIS modelling. We may wish to simply view the surface, which is a great way to understand the surface in general, or we may be interested in specific information about parts of the surface. For example, we might wish to have some information (e.g., altitude, temperature, concentration of a pesticide, etc.) at a given point on the surface.

Apart from querying on surface data values, we might be interested in general information about the surface's shape that is not immediately apparent by simply viewing the surface. For example, we may wish to know the following:

- What points are at the same elevation.
- What parts of the surface face the same direction.
- Where the concentration of a chemical, or the land surface, declines most precipitously.

Other than the aforementioned cases, there are a lot more applications of surface analysis.

Geostatistics

The data that we have are never complete; we have either the wrong kind or insufficient or partial coverage. Naturally, we seek ways to predict the values between, or to extrapolate beyond, the limits of our data. Geostatistics is an application of the theory of random functions for estimating natural phenomena. The basic concept of geostatistics is that of scales of spatial variation. Data which are spatially independent show the same variability regardless of the location of data points.

However, spatial data in most cases are not spatially independent. Data values which are close spatially show less variability than data values which are farther away from each other. A fundamental concept in geography is that nearby entities often share more similarities than entities which are far apart. This idea is often labelled 'Tobler's first law of geography' and may be summarised as 'everything is related to everything else, but near things are more related than distant things'. The exact nature of this pattern varies from data set to data set; each set of data has its own unique function of variability and distance between data points. This variability is generally computed as a function called semivariance.

Geovisualization

Geovisualization (short for geographic visualization) refers to techniques and tools designed to interactively 'visualize' spatial phenomena. In other words, Geovisualization is about GIS data visualization; it refers to the presentation of data by maps, digital images, vector data, DEMs, tabular information, and virtual reality, in either two or three dimensional presentations, static or animated, in soft or hard copies.

A GIS includes interactive maps and other views that operate on the geographic data sets. Maps provide a powerful metaphor to define and standardize how people use and interact with geographic information. Interactive maps provide the main user interface for most GIS applications and are available at many levels, from maps on handheld mobile devices, to Web maps in browsers, to high-end GIS desktop applications. Maps are used to convey geographic information as well as to perform numerous tasks, including advanced data compilation, cartography, analysis, querying, and field data collection.

In addition to maps, other interactive views, such as chart, globe, schematic drawings, and multimedia output, are used as views into GIS databases. The term 'geographic visualization' is also used to describe the use of maps for setting up a context for visual information processing, which can then lead to formulation of research questions or hypotheses, and thus it is not intended to visual representation only, rather a geospatial analysis.