# THE FUNCTIONALITY OF GIS

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*The functionality of GIS is an important topic both academically and practically. This chapter presents an introduction to the generic functionality of GIS and explores the relationship between functionality and application. The basic principles of geographical database design and the main geographical models and structures are discussed along with the types of geographical features. The main body of the chapter is devoted to discussion of a functional classification of GIS. This is a convenient organizing framework for introducing the functionality of GIS. An important theme of this classification is the influence of the data model on functionality. The functional classification follows the logical progression of a GIS project from data capture, transfer and edit, through store and structure, on to restructure, generalize and transform, then query and analyse and, finally, present. The link between GIS functionality and application is then explored. The chapter concludes with some brief comments about the areas of GIS functionality requiring future attention.*

## INTRODUCTION

This chapter aims to provide a basic introduction to the generic functionality of GIS. In the context of this book, it is something of a link chapter which draws together many concepts discussed briefly elsewhere, although a number of new concepts are introduced. Functionality is defined as all the data collection, storage, manipulation, analysis and presentation operations carried out by GIS. The functionality of GIS has been widely discussed in recent years because of its importance in system comparison and classification. Functionality has been used to compare GIS mainly for the purposes of evaluating systems for purchase (Guptill 1988, 1989). Potential purchasers frequently ask software vendors to complete checklists of functions which they use to compare systems. GIS have been classified according to functionality for the purposes of developing a basic understanding and theory of the GIS discipline (GIS World 1990; Maguire and Raper 1990). The idea behind this is that a satisfactory classification of GIS will enable systems to be organized in a common framework using standard terminology. This will greatly facilitate information exchange and will have benefits for all people working in GIS. System comparisons, education and training, and the development of core GIS theory will all benefit from a better understanding of the relationship between systems and the use of standard terminology.

This chapter is based heavily on the work of Dangermond (1983) and Maguire and Raper (1990), although their ideas about GIS functionality are updated and extended to take into consideration new developments in the discipline. At the outset it must be acknowledged that it is very difficult to produce a clear and comprehensive description of GIS functionality for two main reasons: (1) GIS is a relatively youthful and rapidly evolving discipline and any models of the discipline are bound to date rapidly; (2) the applications of GIS are many and varied and any scheme will have to satisfy a very heterogeneous group of individuals. As a consequence of these two factors GIS is beset by problems of lack of standard terminology. The scheme presented here is, therefore, of necessity relatively general. It does not relate to any one system in particular, rather the attempt is to develop a generic high level scheme with widespread applicability.

This chapter is arranged in five sections. The first two introduce the ideas of geographical data models, data structures and geographical features which are central elements of the discussion. The third section is the most substantial and describes the generic functionality of GIS. The relationship between functionality and application is examined in the next section using four different application areas. Finally, some conclusions are drawn about the current status of GIS functionality.

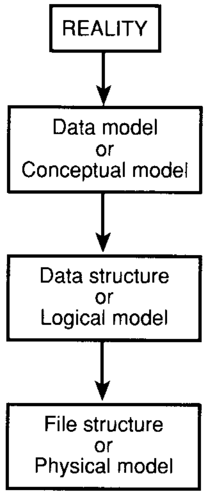


**Fig. 21.1** Levels of abstraction relevant to geographical databases (after Peuquet 1984).

## GEOGRAPHICAL DATA MODELS AND STRUCTURES

In order to appreciate the reasons for including certain types of functions in GIS it is necessary to understand the basic principles of geographical database design and data models. Like many areas of GIS, there is some confusion over terminology here. The simple and unambiguous conceptual description of geographical databases expounded by Peuquet (1984) is a useful reference which will be used in this discussion (see also Goodchild 1991 in this volume; Guptill 1991 in this volume). Peuquet suggests four levels of abstraction are relevant to geographical databases (Fig. 21.1): reality – the phenomena as they actually exist, including all aspects which may or may not be perceived by individuals; data model (sometimes called a conceptual model) – an abstraction of the real world which incorporates only those properties thought to be relevant to the application in hand, usually a human conceptualization of reality; data structure (or logical model) – a representation of the data model which reflects implementation issues and is often expressed in terms of diagrams, lists and arrays designed to reflect the recording of the data in computer code; file structure (or physical model) – the representation of the data in storage hardware.

In a geographical data model, reality (the real world) is represented as a series of geographical features (sometimes called entities or objects, but the term 'features' is preferred here to avoid confusion with other uses of these terms). The nature of geographical features is examined in the next section.

Creating a data model involves sampling the continuous or analogue space of reality and representing it in a discrete form (Fig. 21.2). Two fundamental geographical data models are used in designing geographical databases. These are referred to as the vector and tessellation (also called raster) models (Peuquet 1984; Egenhofer and Herring 1991 in this volume). There has been much debate over the past decade or so about the relative merits of both these systems, because the type of data model employed has a profound impact on the conventions and procedures of GIS. The selection of data model is influenced by many factors including the software available, the nature of the application, the training of the individual and historical precedent (Burrough 1986; Aronoff 1989; Star and Estes 1990).

Although the terms raster and tessellation are often used synonymously, strictly speaking a raster is a geographical data structure and only one method of implementing the tessellation geographical data model. In the tessellation model, geographical features are described as polygonal units of space in a matrix (also called a mesh, lattice or array). Usually, the polygonal units are regular squares referred to as pixels (derived from the term

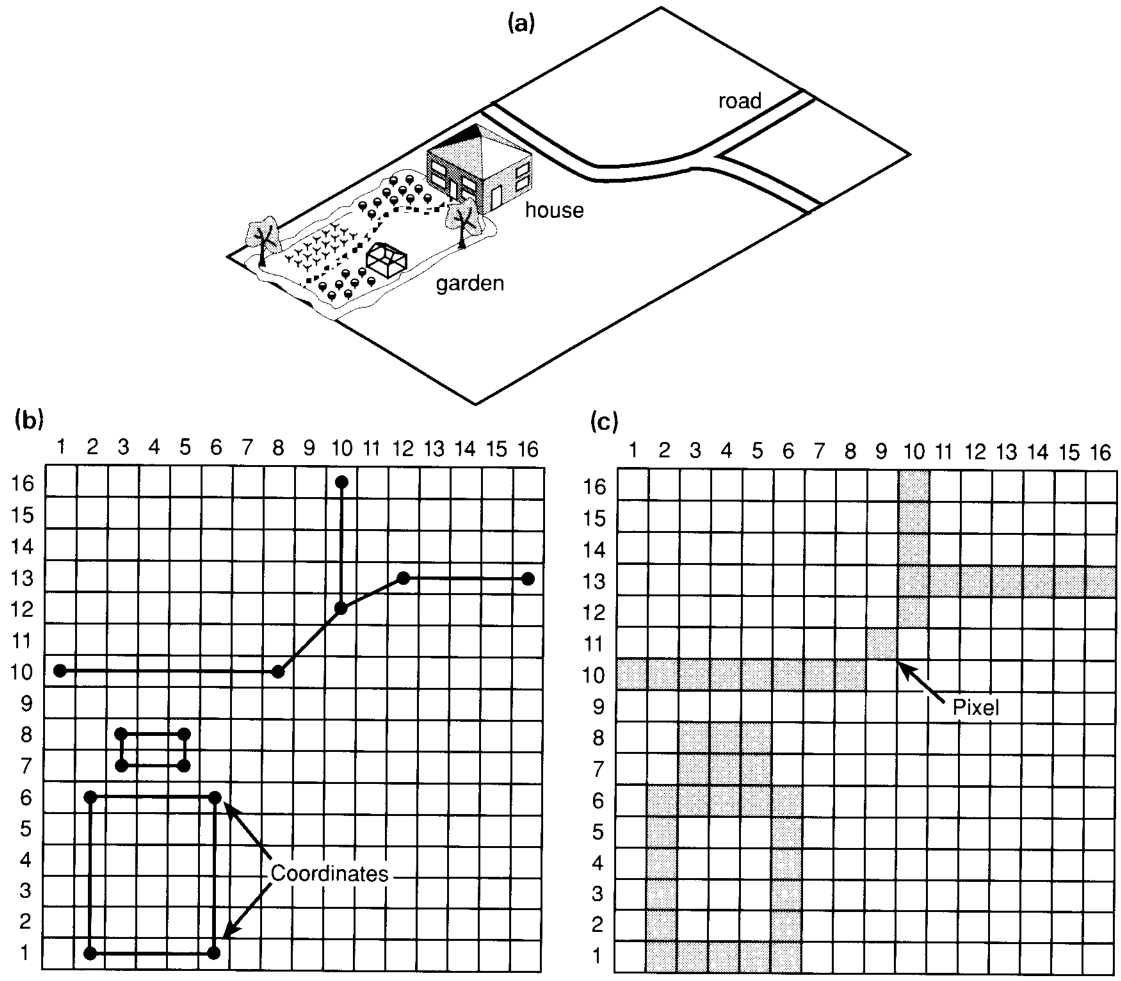


**Fig. 21.2** Vector and tessellation data models (after Maguire 1989).

'picture element'), but regular and irregular triangles and hexagons have also been used (Peuquet 1984). Where the cells are organized such that they are stored in line scan order, the term *raster* can properly be used, but it is frequently applied to any unstructured tessellation model and it is in this more common general form that it is used here. At a general level, the tessellation model is conceptually simple, it is readily implemented on inexpensive microcomputers and it offers a relatively quick method of developing GIS analytical operations. The data model is area oriented in that greater emphasis is placed on the contents of areas rather than the boundaries between them. Boolean operations are easily incorporated into this model, as are many types of simulation (e.g. the impact of acid precipitation on woodlands, variations in groundwater caused by water extraction from aquifers or the impact of freight transport costs on factory location). It is difficult to represent boundary or line operations using the tessellation model and many socio-economic applications, which place great emphasis on these types of geographical feature, are not easily accommodated. The tessellation model tends to be favoured by researchers interested in environmental applications.

In the vector model, geographical features are represented as a series of $x,y$ or $x,y,z$ coordinates (Fig. 21.2). The vector model is much more complex than the tessellation model and is less readily adaptable to cheap microcomputer technology. Data collection and structuring using this model are on the whole more time consuming.

The boundary-oriented nature of the model has led to its use in a variety of socio-economic applications, especially those involving variable density phenomena (e.g. population characteristics), networks, coordinate geometry and high quality cartographic operations. The complex organization means that many analytical operations, such as polygon overlay and buffering, are conceptually complex and computationally intensive.

## GEOGRAPHICAL FEATURES

In GIS, geographical features are usually defined according to their two data elements. The geographical (also called locational) data element is used to provide a reference for the attribute (also called statistical or non-locational) data element. For example, administrative boundaries, river networks and point locations of sites are all geographical features used to provide a reference for, respectively, census counts, river water flows or site elevations. In GIS the geographical element is more important than the attribute element and this is one of the key features which differentiates GIS from other information systems.

Four generic geographical features are normally recognized on the basis of Euclidean dimensionality: points, lines, areas and surfaces (Unwin 1981; DCDSTF 1988; Maguire 1989; Gatrell 1991 in this volume). In this scheme, points have no length dimension and are said to have a dimensionality of zero. Lines have a single length dimension and dimensionality of one. Areas have two length dimensions and dimensionality of two. Finally, surfaces have three length dimensions and are given a dimensionality of three. All these features can be represented in either the tessellation or vector models.

Each of these generic geographical features may be further subdivided according to the characteristics of the associated attribute data (Table 21.1). For example, points might be subdivided into houses, telephone boxes and soil pits; areas might be sub-divided into those with a population density of, say, 0–5000, 5001–10 000 and greater than 10 000 persons per square kilometre; and surfaces might be subdivided into those which are flat, steeply sloping and very steeply sloping.

There are various ways in which attribute data can be classified, the most widely used being the level of measurement (Stevens 1946). Stevens proposed the fourfold classification of Nominal, Ordinal, Interval and Ratio. Nominal data have only sufficient information associated with them to classify them into categories. For example, rocks can be classified as granite, limestone and schist, etc. Ordinal data contain sufficient information so that they can be ranked in ascending or descending order. For example, some social classifications seek to classify households by the occupation of the household head. People in professional occupations are usually placed in class 1, semi-professional in class 2, manual in 3, etc. Interval data have the property that distances between categories are defined as fixed equal size units. Thermometers, for example, measure temperature on an interval scale, ensuring that the difference between, say, 20 °C and 25 °C, is the same as that between 0 °C and 5 °C. However, because the scheme lacks a fixed zero only differences and not absolute values can be measured. Ratio data have in addition an absolute zero. A value of 0 mm of rainfall indicates no rainfall, whereas 0 °C does not indicate no temperature! It is possible to calculate ratios from data measured at the highest level. For example, 1000 mm of rainfall is twice as much as 500 mm, but it is not sensible to say that 50 °C is twice as warm as 25 °C. For most practical purposes in GIS the interval and ratio categories can be treated as one.

The dimensionality and levels of measurement classifications are usually linked together to give a two-dimensional table showing the basic types of

**Table 21.1** A classification of geographical data (after Robinson *et al.* 1984; Unwin 1981). The maps are described according to the type of symbolism which can be used.

| | **Point** | **Line** | **Area** | **Surface** |
|---|---|---|---|---|
| Nominal | Dot | Network | Colour class | Freely coloured |
| Ordinal | Ordered symbol | Ordered network | Ordered colour | Ordered colour |
| Interval /ratio | Graduated symbol | Flow line | Choropleth | Contour |

data used in GIS (Robinson *et al.* 1984; Unwin 1981) as shown in Table 21.1.

Unfortunately, there are several problems in applying this simple classification. The dimensionality component fails to incorporate four important ideas. First, there is no provision for networks which are more than a collection of lines and, therefore, require a richer means of representation. Secondly, some geographical features can only be defined by reference to a pair of features (Goodchild 1988). For example, the exact position of many underground streams in limestone regions is unknown: the streams can be defined only in terms of the points at which the streams disappear (sinks) and reappear (springs). Thirdly, the definition of features as points, lines and areas is scale dependent. A city, for example, might be represented as a point on a small-scale map, or an area on a large-scale map. Fourthly, this view of features comprising points, lines, areas and surfaces is at variance with our everyday experience where geographical features are viewed as complete units. A forest, for example, is often not considered a collection of points, lines and areas, or even a collection of trees, but in many cases a single atomic feature. Object-oriented data modelling, although still in its early stages, offers some interesting possibilities for assisting in representing features in geographical databases (Egenhofer and Frank 1987; Worboys, Hearnshaw and Maguire 1990). Fifthly, this classification fails to incorporate the temporal dimension. Many of the processes which people wish to encapsulate in GIS can best be represented using some type of space–time model or geographical data matrix (Berry 1964; Dangermond 1983). Time can be considered a fourth dimension and in some instances it can be more important than the geographical component (Fig. 21.3). To date, there have been few attempts to incorporate time into GIS (Langran and Chrisman 1988), though it is certain to increase in importance. Chrisman (1991 in this volume), drawing principally on the work of Sinton (1978), shows how geographical phenomena can be modelled from their geographical (or locational), attribute (or thematic) and temporal components. In geographical modelling, one of these components must be fixed, the second allowed to vary and the third measured. For example, in a study of the socio-economic characteristics of a city using population census data, the year is normally fixed, the location allowed to vary (population is usually reported for census tracts) and the socio-economic characteristics of the population are measured. This simple but powerful model offers a very useful organizing framework for geographical enquiry. Finally, a new challenge for GIS software developers and data modellers is how to represent sound and pictures as well as conventional data types in what might be termed multi-media GIS (Shepherd 1991 in this volume).

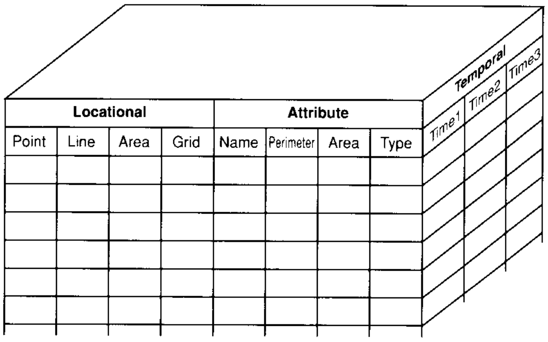


**Fig. 21.3** The geographical data matrix used as the basis for much geographical enquiry (after Dangermond 1983).

There are also two problems associated with the level of measurement classification. First, the simple Nominal, Ordinal, Interval and Ratio scheme gives no explicit provision for incorporating a count data type, such as the number of people in a census area with a particular disease. This is important because in some statistical modelling procedures count data must be considered quite differently from other data types (Flowerdew and Green 1989; Flowerdew 1991 in this volume). Secondly, in the case of areas it is important to distinguish between density measures (e.g. population density) and absolute measures (e.g. the number of people). These have an important bearing on the type of analyses that can be conducted (Unwin 1981; Flowerdew and Openshaw 1987) and, again, these ideas cannot easily be incorporated into the level of measurement classification.

In spite of these problems, which in some cases may be very significant, in the absence of any real alternative the dimensionality/levels of measurement typology remains the principal method of classifying geographical data.

This mode of thinking is predicated on the view that the part of reality designated as the study area for database purposes can be conveniently subdivided into discrete atomic features and that these features do not overlap. This process is termed *planar enforcement*. It is assumed that geographical features can be easily defined and classified. In some cases, mainly features created by humans, this assumption is valid, but in others it can only be applied with difficulty. It is, for example, very difficult to define the edge of an urban area or the boundary between soil types, because they do not occur sharply. This problem has long been recognized in geography and is not new to GIS. The field of fuzzy logic, which has received only scant attention from GIS workers, offers a potential alternative to the strict use of planar enforcement (Robinson, Miller and Klesh 1988; Burrough 1989). A further problem with this view of GIS is that it is fundamentally reductionist since it focuses attention on the differences rather than the similarities between individual elements. Given the nature of the problems which GIS are often used to tackle, a holistic approach might be more appropriate, but no one as yet has investigated how this might be achieved.

In summary, geographical features are represented in geographical databases as collections of geographical and attribute data. The present classification of geographical features, according to the dimensionality of the geographical data and the level of measurement of the attribute data, is universally used in the absence of any real alternative and despite some significant problems.

## THE FUNCTIONALITY OF GIS

This scheme of GIS functionality is primarily based on the work of Maguire and Raper (1990) which in turn draws on Dangermond (1983) among other sources. The scheme is intended as a top-down hierarchical classification of the major types of functions which characterize GIS. It therefore embodies only the most important and widely used generic functions. Further details about these and other lower level functions may be found in publications such as Guptill (1988) or GIS World (1990). Specific details of how individual functions are implemented in GIS software can be obtained from appropriate system manuals.

In the proposed scheme ten major categories are identified (Fig. 21.4). These follow the logical progression of data in a GIS project: (i) capture; (ii) transfer; (iii) validate and edit; (iv) store and structure; (v) restructure; (vi) generalize; (vii) transform; (viii) query; (ix) analyse; and (x) present. Some of these major categories are subdivided on the basis of whether the functions deal with geographical or attribute data. A further level of subdivision uses the data structure employed. The vector and tessellation models (and their implementation as data structures) exert a fundamental conceptual and practical influence on the designers and users of GIS and so it is appropriate that they are given prominence in functional GIS classifications. It is, of course, impossible to develop a scheme of GIS functionality which is completely comprehensive. The heterogeneous nature of GIS means that systems have been developed and adapted to perform many different functions. There are also considerable problems of defining exactly what is meant by terms such as 'overlay', 'object orientation' and 'search'. While the functionality classification scheme follows the progression of data in a GIS project from capture to present, in any GIS project not all of the GIS functions, or even all of the major categories need be employed. It is also likely that a number of functions will be applied to the same data set several times. For example, during data integration a data set may be edited, generalized and transformed several times before it has satisfactory characteristics.

### Capture, transfer, validate and edit

Capture, transfer, validate and edit are used to acquire and load error-free digital data into GIS. These functions are crucial to GIS since data capture is often one of the biggest bottle necks and most expensive GIS tasks. Many different techniques and devices are available for both geographical and attribute data (Rhind 1974; Marble, Lauzon and MaGranaghan 1984; Chrisman 1987; Maguire 1989; Jackson and Woodsford 1991 in this volume). Primary geographical data collection, using raster remote sensing systems (such as scanners and radars) and vector Global Positioning Systems (GPS) and field surveying, is employed in areas which have yet to be mapped and for updating existing digital databases. Since most of the world has now been mapped (Parry and Perkins 1987), secondary geographical data collection devices are now used more frequently for collecting digital data. However, given the comparatively low cost of data collection using GPS, this primary data collection method may replace secondary digitizing in the future. Secondary geographical data collection devices include raster scanners and vector semi-automatic table digitizers for 2-D data, and stereoplotters for 3-D data. Attribute data are collected using a plethora of different devices. These include automatic and semi-automatic data loggers, as well as keyboards and, increasingly, Optical Character Readers (OCR) and voice-recognition systems.

Transfer involves moving previously captured data into GIS, using electronic networks or magnetic media. A number of system-dependent and system-independent formats exist for both geographical and attribute data. For geographical data, system-dependent formats include ARC/INFO export format, INTERGRAPH Standard Interchange Format (SIF) and AUTOCAD DXF (see Guptill 1991 in this volume for further details of data transfer). System-independent formats for geographical data include the United States Geological Survey (USGS) Digital Line Graph (DLG), the US Bureau of the Census TIGER (Topological Integrated Geographic Encoding Referencing) format and the UK National Transfer Format (NTF). For attribute data, system-dependent formats are used infrequently. Instead there is a preference for the principal system-independent format, the American Standard Code for Information Interchange (ASCII). The choice of whether capture or transfer should be used to obtain digital data depends upon the cost and availability of data from other agencies relative to in-house collection. As the digital mapping programmes of national mapping agencies and the global monitoring satellite programmes progress (see Clark, Hastings and Kineman 1991 in this volume), data transfer is likely to increase in importance as the costs of map and document digitizing and scanning decrease.

Whether the data have been captured or transferred, they must be validated and, if necessary, edited to remove errors and inconsistencies. All good GIS software systems have routines for validating and editing geographical features. Database Management Systems and standard computer system editors are usually employed to validate and edit attribute data. In order to validate data it is necessary to check the data against an original and look for unusual values. This might involve producing a test plot or some statistics describing the data using some of the plotting and summary functions described later.

## Store and structure

Data storage and structuring is a crucial stage in creating a geographical database using GIS. In the main, structuring is undertaken because structured data can usually be stored more efficiently and can support high levels of analytical operations more easily. As Maguire and Raper (1990) demonstrate, the type of data structure employed determines the range of functions which can be used for manipulation and analysis. Furthermore, transfer between structures (restructuring) is time consuming, expensive and error prone. A simple classification of the main schemes for structuring geographical and attribute data in GIS is presented in Fig. 21.4. Space does not permit a detailed review of each of them and in any case they are discussed extensively in Peuquet (1984), Aronoff (1989), Maguire and Raper (1990), Samet (1990) and Egenhofer and Herring (1991 in this volume). The raster-vector dichotomy is examined by Davis and Simonett (1991 in this volume) and Egenhofer and Herring (1991 in this volume). This aspect of the classification of GIS functionality is probably least well developed in the literature, principally because of the variety of structures available and terminology problems.

The major subdivision of geographical structures is into tessellation, vector and hybrid types. The tessellation structures are further subdivided into regular and irregular. Regular geographical tessellation structures include: unstructured schemes such as bitmaps and grids; simple structures such as rasters which are ordered by line scan, run length encoding methods, Morton ordering, etc.; and a whole host of hierarchical methods such as quadtrees, KDB-trees, octrees, etc. The main irregular method is the Triangulated Irregular Network (TIN) which is used to represent surfaces using triangles (Weibel and Heller 1991 in this volume).

Vector structuring techniques can be divided

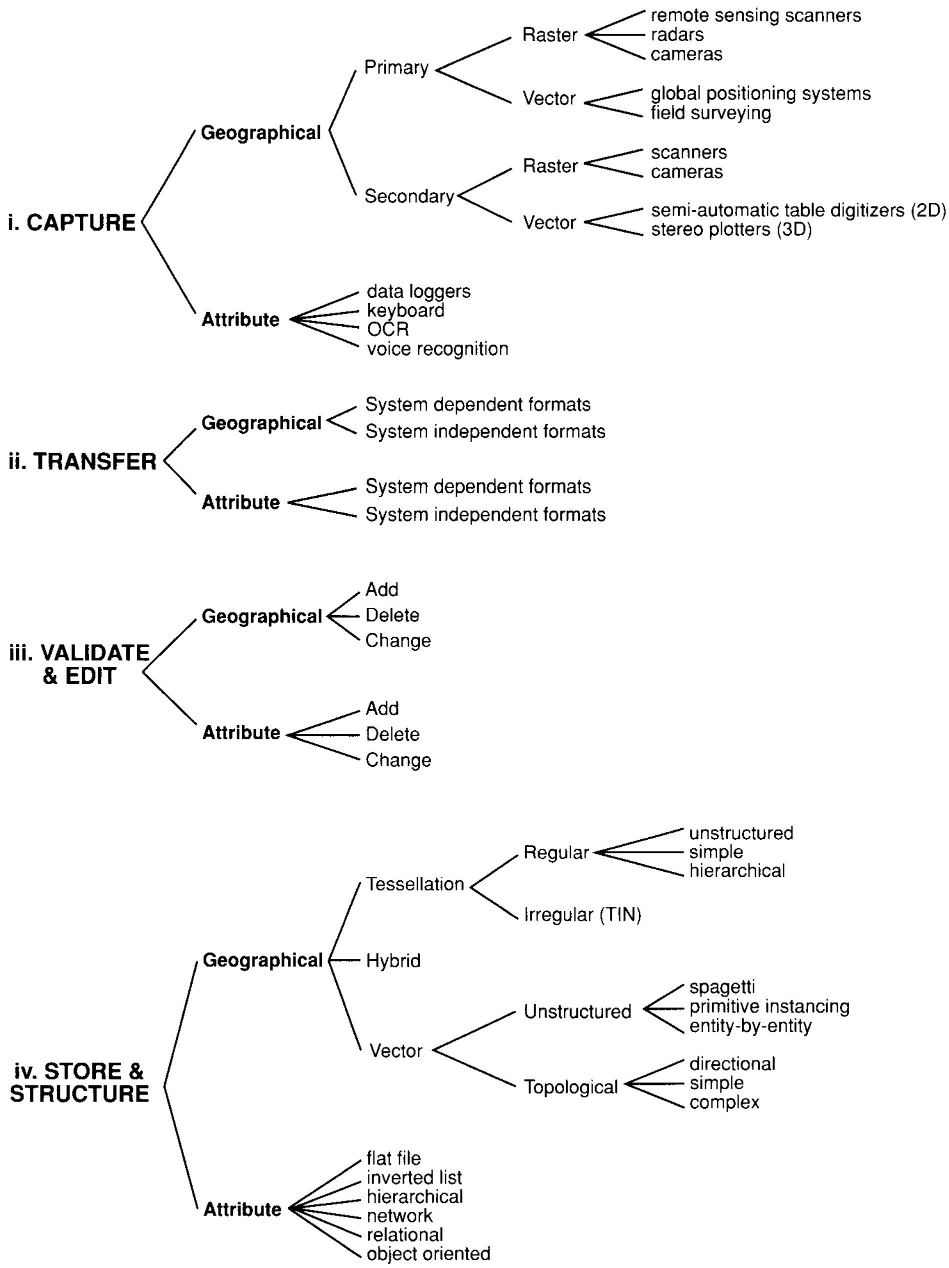


**Fig. 21.4** The functional components of GIS (after Maguire and Raper 1990).

into unstructured and topological types. The former can be subdivided into the 'spaghetti', primitive instancing and entity-by-entity structures. The spaghetti structure is so called because the geographical features are represented as a simple collection of points and lines (also called links and nodes), analogous to a plate of spaghetti. Primitive instancing was developed primarily in Computer Aided Design (CAD) systems. In the database the basic elements are symbols representing buildings, roads, traffic lights, etc., which can be moved interactively and positioned at any appropriate location on a map. The entity-by-entity structure codifies geographical features as complete units, for

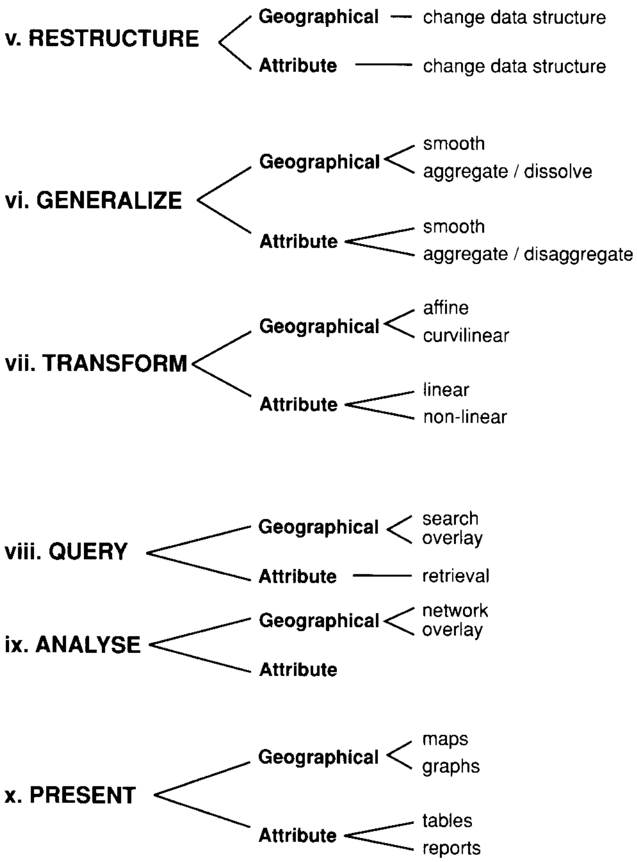


**Fig. 21.4 (continued)** The functional components of GIS (after Maguire and Raper 1990).

example as closed polygons, but no topological information is included. Such unstructured approaches are very useful for drawing simple maps and diagrams, but the absence of any structure within the data severely limits analysis. Topological data structures facilitate many types of geographical query and analysis such as retrieving adjacent areas and undertaking network analysis. Three types of topological structure are frequently identified. Directional topological systems, such as the US Bureau of the Census DIME system (Corbett 1979), record topology along with the direction of a line segment. Simple topological relationships are present in systems such as POLYVRT developed at the Harvard Laboratory for Computer Graphics and Spatial Analysis and incorporated in the ODYSSEY GIS and later systems. More recent systems such as ESRI's ARC/INFO and GeoVision's GIS use a fully topological structure.

The vaster structure was the first hybrid structure developed to make use of the advantages of both the vector and tessellation models (Peuquet 1984). In this model the basic unit is the swath which corresponds to a series of contiguous scan lines in a raster scheme. Each swath has a raster and a vector component allowing the logic of both systems to be used during processing. Although the vaster has found little favour with software developers, a number of other hybrid data structures have now been implemented. In large geographical databases it is quite common for quadtree indexing to be used to organize vector topological data. There have also been attempts to use vector indexing to store tessellation data.

Five main data structures have been used to organize attribute data in GIS: flat file, inverted list, hierarchical, network and relational (Healey 1991 in this volume). Flat files have a very simple 'card box' like structure and files cannot easily be related to each other. Because of this, flat files are seldom used in anything other than simple GIS. In the inverted list structure the row ordering of records has significance for retrieval. Key search fields are identified and these are used to create an inverted list (a secondary index) to data storage locations on a disk. Although not widely used in GIS, largely due to their restriction to large IBM mainframe computers, they have the advantage of being relatively fast at data retrieval. The hierarchical structure is a type of tree in which each feature can have several links to lower elements in a hierarchy, but only one link to a higher record. This system is useful for implementing one-to-many relationships, but it cannot adequately deal with many-to-many relationships. This lack of flexibility has restricted its use in GIS. The network structure overcomes the main limitation of the hierarchical structure by including a capability for many-to-many relationships at all levels. This model is comparatively efficient, but its complex structure has restricted its use in creating geographical databases. The relational model has a comparatively simple structure. Data are organized into a series of tables which are linked together by common key fields. Relational databases are generally thought to be easy to understand and set up. As a result of their widespread adoption in many application areas, relational database management systems have been used extensively in GIS.

The data structures discussed above have a number of inherent problems which limit their use for geographical database design. They do not easily allow incorporation of both simple and complex geographical features (e.g. points, lines, polygons, sets of polygons and rasters). Current systems do not have facilities for supporting multiple versions of the same feature, as would be necessary to create a database covering different time periods. The machine-oriented nature of existing systems also makes it difficult to model complex problems. The slow speed of systems based on proprietary DBMS is a further disadvantage. Object-oriented database design already discussed above is one possible approach which may alleviate some of these problems.

All the main structuring methods are used by at least one proprietary GIS software system. The ways in which geographical and attribute models are linked together in proprietary GIS systems is described elsewhere in this book (Healey 1991; Maguire 1991).

The process of storing and structuring geographical and attribute data in GIS may be achieved in several different ways. In some systems the data are structured at the time of digitizing by requesting the necessary information from the person digitizing. Other systems can structure data in a batch process from unstructured or partly structured data. A number of the automatic data collection devices, such as scanners, have associated software which also structure data as they are collected. Because it is so time consuming to structure data by hand, it is preferable to automate the operation as far as possible.

### Restructure, generalize and transform

Data manipulation is a key area of GIS functionality since it allows data from disparate sources to be converted to a common format for analysis. This process is sometimes termed data integration (Flowerdew 1991 in this volume). The most important operations are restructure, generalize and transform.

Restructure involves changing the data structure used for the geographical and/or attribute data. In the case of geographical data, this usually means converting data between one of the vector and one of the tessellation structures. Peuquet (1981a, 1981b) reviews the principal approaches to restructuring geographical data and points out that vector–raster restructuring is considerably simpler and faster that raster–vector restructuring. All restructuring is time consuming, computationally intensive and, potentially, error prone and thus should be avoided, if at all possible. Unfortunately, there are still no truly integrated GIS which can analyse both vector and tessellation data simultaneously. Current systems employ the technique of restructuring either the vector or tessellation data to make them compatible.

Generalize includes both smoothing and aggregating features and their inverses (Muller 1991 in this volume). Several different functions exist for tessellation and vector data. They include line and grid smoothing, dissolving the boundary between two adjoining polygons to create a single larger polygon, and replacing attribute values by their mean. Generalization is still poorly developed in GIS and it will be a considerable time before automatic one-pass generalization of geographical data from, say, a scale of 1 : 10 000 to a scale of, say, 1 : 1 000 000 is possible. Current GIS only provide functions for operations such as weeding coordinates from lines or aggregating pixels with similar values.

Transformation of geographical data involves affine transformations of scale, rotation, translation and inversion, and curvilinear transformation of the type used to change between map projections. Map projection transformations tend to be most important in large countries, particulary those in high latitudes, and also in applications which use a wide variety of data types. They may be applied equally to both tessellation and vector data, although the mathematics and algorithms are quite different (Maling 1991 in this volume). Transformation of attribute data includes the application of linear and non-linear functions and constants, such as might be found in most basic statistical analysis packages (e.g. Minitab, SPSS and GLIM).

## Query and analyse

To many it is query and, more especially, analysis that are at the heart of GIS. It is the ability to analyse geographical patterns and relationships which differentiates GIS from other computer systems, such as those used for computer cartography, computer-aided design, remote sensing and database management (Maguire 1991 in this volume). The classification of functions into the two groups, query and analyse, is somewhat simplistic since individual functions often overlap one or more groups. The difference between the two is really one of emphasis. Query functions are concerned with inventory questions such as 'Where is...?' Analysis functions deal with questions such as 'What if...?' Nevertheless, this binary classification is a useful organizing principle.

Spatial query and analysis necessitate distance and direction operations on spatial data. Query involves the retrieval of attribute data about spatial features. At its simplest it involves pointing at a feature and retrieving its name, but it can also involve retrieving all the attribute information about features within a certain distance of a feature or within a study area which has a complex shape. These operations use such functions as spatial searching and overlay. Spatial searching (also called buffering or proximity analysis) can be used to highlight a zone of interest around a point, line, area or cell feature which can then be used to retrieve attribute data or generate a new spatial feature. Overlay is the process of comparing spatial features in two or more map layers. For example, information about land suitability for housing development may involve comparing information on land ownership, land prices, building restrictions, geology, etc., all of which could be stored in separate data layers. When search and overlay are combined with query and comparison operations on attribute data, complex analysis can be undertaken. Examples include network routing, location allocation modelling, terrain intervisibility calculation and surface flow modelling. Certain types of operations are best carried out on data structured in different ways. For example, overlay and buffer calculation are most easily carried out using data structured as a grid or raster (Berry 1987, 1991 in this volume; Tomlin 1991 in this volume), whereas network analysis and high quality map production are best carried out on data structured using the vector system.

The process of relating geographical features on different data layers is often referred to as map algebra or map processing (Tomlin 1983, 1991 in this volume; Berry 1987) and its origin lies in the work of McHarg (1969) who first described its manual implementation. At its simplest, map processing involves the interaction of a single geographical feature and a single operator (also called a function). More often it involves relating at least two geographical features by overlay, on more than one map layer and using one or more operator(s). Berry (1987) suggests that overlay map processing encompasses point, neighbourhood and region operations. Point processors consider each geographical feature independently and can be conceptualized as 'vertically spearing' a series of features from a stack of co-registered data layers. Regional processors associate each location with a set of other locations having a similar characteristic. The features within the boundaries of each template become available for processing. Neighbourhood processors identify features for processing in terms of their spatial proximity (e.g. all features within 100 metres of a road). The map processing concept was developed for, and is still typically applied to, raster databases, but there seems no reason why the same concept cannot also be applied to vector databases. The results of map processing are usually output in the form of another map.

Defining the operators, particularly the minimum set, used in GIS analysis has been the subject of much debate. Freeman (1975) defined a set of 13 operators: left of, right of, beside, above, below, behind, in front of, near, far from, touching, between, inside and outside. Feuchtwanger (1989) listed only six: adjacency, proximity, subdivision, overlap, nearest neighbour and sub-region. Egenhofer and Frank (1987) used just four: neighbour, inclusion, distance and direction. The minimum set of spatial operators for defining topological relationships between spatial objects has been suggested by Peuquet (1984) as: distance, direction and the Boolean set operators of intersection, union and complement. In his examination of the logical principles of GIS, Robinove (1986) argues that GIS analytical operations can be described using the relationships of classes (types of geographical features) based upon the calculus of propositional functions (traditional rules of symbolic logic). He explains the logical relations of spatial position in terms of adjacency, proximity or connectedness, superposition and containment, together with the Boolean and statistical and mathematical operators.

Specific details of the action of geographical operators are given in Dangermond (1983), Burrough (1986), Berry (1987), Guptill (1988) and Tomlin (1990, 1991 in this volume).

The degree of integration of geographical and attribute data describing geographical features exerts an important influence on the way query and analysis operations are carried out and the results that are obtained. In simple systems, where the geographical and attribute data are not closely integrated and only a single attribute is associated with a geographical feature description, it is only possible to combine either the geographical or the attribute components. In more sophisticated systems where the two components are closely integrated and multiple attributes can be associated with a geographical feature description, an operation on one component results in a corresponding operation which updates the other component and thus maintains their referential integrity. For example, in closely integrated vector systems it is possible to join points, lines and areas on two coverages together by overlay, as well as some, or all, of their associated attributes. To date, only vector systems closely integrate geographical and attribute data components, but there is no theoretical reason restricting raster systems.

## Present

The final stage in any GIS project is the presentation of the results. Geographical data can be presented in many forms, including maps, graphs, statistical summaries and reports, tables and lists. All of these methods of output should ideally be provided by a GIS. Though presentation is a vital part of any substantive application and one which can require access to a wide range of commands, technically it is much less sophisticated than some of the other functions discussed earlier. At the presentation stage, GIS are acting much like DBMS report generators and computer cartography systems. The emphasis is on formatting output and flexibility of display in, for example, a range of different colours, symbol types, high quality fonts and shading schemes. The best GIS offer users an interactive environment within which to experiment with the appearance and content of maps and graphs.

## FUNCTIONALITY AND APPLICATION

It is not uncommon for GIS software systems to have several hundred functions because of their general purpose nature. Specific applications, not surprisingly, often use only a small selection of the overall functions. In this section four applications, which are representative of the overall spectrum, are used to illustrate the relative importance of different functions in certain contexts. For the purposes of this discussion it is assumed that all the applications are being carried out in an area with similar geographical characteristics. The relationship between functionality and application for a few example applications is summarized in Table 21.2.

### Hazardous vehicle routing

The routing of vehicles carrying hazardous waste along the national road network is undertaken in many countries. In GIS terms there is an obvious need for a geographical database containing a description of the national road network. Even in relatively large well developed countries this is likely to constitute only a relatively small amount of data and so data capture, transfer, validate and edit are unlikely to be of critical importance. Network routing is best carried out on a database with the geographical data structured using the topological vector model, but since small quantities of attribute data are utilized the choice of structure for the attribute data is less important. It is unlikely that restructure, generalize and transform will be required in hazardous vehicle routing. Some limited query functions may be needed to locate the name of a road, junction or low bridge for example. The most important functions are likely to be those concerned with analysis and, in particular, network routing. This will involve the use of shortest path algorithms where impedances to movement are attached to the roads or road junctions. Output from the results of analytical operations is likely to be simple maps and reports giving directions and warning of obstructions.

### Land ownership monitoring

Land ownership is a fundamental component of civilized societies (Dale 1991 in this volume). In

**Table 21.2** The relationship between functionality and selected applications expressed on a scale of 1 (insignificant) to 5 (very significant).

| | Hazardous vehicle routing | Land ownership monitoring | Forest resource management | Census map production |
|---|---|---|---|---|
| 1. Capture | 2 | 5 | 3 | 4 |
| 2. Transfer | 2 | 4 | 2 | 2 |
| 3. Validate and edit | 2 | 4 | 3 | 3 |
| 4. Store and structure | Topological vector | Entity-by-entity vector | Tessellation grid | Spaghetti or entity-by-entity vector |
| 5. Restructure | 1 | 1 | 5 | 1 |
| 6. Generalize | 2 | 1 | 5 | 4 |
| 7. Transform | 1 | 1 | 3 | 1 |
| 8. Query | 3 | 5 | 4 | 3 |
| 9. Analyse | 5 | 1 | 3 | 1 |
| 10. Present | 2 | 2 | 3 | 5 |

highly populated countries, creating an inventory and monitoring ownership are significant problems for which GIS are frequently used. A land ownership or cadastral information system basically requires a database containing an accurate description of the boundary of a large number of land parcels, together with fast access to a relatively small quantity of attribute data about the owner. The system must be capable of logging large numbers of transactions as land is bought and sold. The geographical data must be held in vector format, but nothing more complex than the entity-by-entity structure is really needed. The need for rapid retrieval and update of relatively small quantities of attribute data means that an inverted list or hierarchical structure may be preferable. Because land parcels tend to be small, there is likely to be a very large number of them, and so data capture, transfer, validate and edit are usually seen as important. There is unlikely to be much call for restructure, generalize and transform. The key operation in land ownership monitoring is query. This might involve searching the database by parcel coordinates, size, parcel name, owner's name, etc. The functions for presenting such simple data need not be sophisticated.

### Forest resource management

The management of forests and similar natural resources poses a number of different questions for the developers and operators of GIS. Natural resource management applications tend to require many types of different data which are reported on disparate spatial bases and which are easily definable. For example, identifying suitable land for planting sitka spruce trees involves the integration of data on climate, soils, existing vegetation, water, slopes, etc. Many of these data can be obtained by classifying satellite data. The need to compare data from many sources and to incorporate raster format satellite data means that most natural resource management applications utilize the raster or grid data structure for database design. Requirements for data capture, transfer and validate/edit are likely to be relatively modest, but costly because of the large number of data layers required for analysis and because of the expense of purchasing satellite data. Restructure and generalize, and to a lesser extent transform, are likely to be very important because of their role in integrating disparate data. Query and analyse are the key operations, their relative importance depending on the use of the system for resource inventory, monitoring and management. Present is of average significance and although sophisticated maps are rarely required, the level of detail on such maps often necessitates advanced functions and technology for display.

### Census map production

Many GIS are basically used for map production, be it in a national mapping agency concerned with topographic maps or a private company concerned with producing thematic maps of population census data (Rhind 1991 in this volume). Census mapping places emphasis on the presentation rather than the query and analysis of information. Because of the limited analytical requirements and the need for high quality output, a simple vector format is preferred such as the spaghetti or entity-by-entity structure. The small size of the basic census areas and the large amount of attribute data mean that capture, transfer and validate/edit are often of considerable significance. While there is little need to restructure and transform the data, the large data volumes and requirement for both large- and small-scale maps mean that generalize is important. There is limited application for query and, especially, analyse, but present is of primary importance.

## CONCLUSIONS

This chapter has presented a brief overview of the generic functionality of GIS. Many specific examples of the use of GIS functions are given in other chapters in this book, especially those in Section III. The classification of GIS functions is important because it facilitates the comparison of systems and should assist in developing a set of standard terminology.

It is clear that there is an important link between the way in which data are structured in a geographical database and the type of functions that can best be employed. The database design stage of a GIS project is especially important because none of the current proprietary GIS software systems can satisfactorily handle both vector and tessellation data analysis simultaneously. Furthermore, restructuring geographical data is time consuming and error prone.

There are many different application areas which can benefit from using GIS and each requires a different set of functions. However, for commercial reasons the majority of GIS software vendors have attempted to develop systems with a wide range of sophisticated functionality. In some cases this leads to over-complex data structures and functions being used for certain applications. This problem is further compounded because the expense of data capture and the fact that departments in large organizations often share the same database, means there is a tendency to collect all possible types of data and to structure them in the most sophisticated way.

Although most current GIS projects are constrained by data collection and staffing difficulties, it would be wrong to assume that there are no gaps in the functionality of current systems. Maguire (1990) sets out a research agenda for GIS for the 1990s. Three key areas requiring attention are concerned with spatial analysis, integrated GIS and network processing. Incorporation of spatial analysis in GIS would allow probabilistic statements to be made about the outcome of GIS operations and, in particular, the magnitude of errors to be estimated (Openshaw 1991 in this volume). The development of truly integrated GIS would allow simultaneous query and analysis of both tessellation and vector data rather than restructuring. The development of network processing would allow more sophisticated utility and transport networks to be modelled.

## REFERENCES


**Aronoff S** (1989) *Geographic Information Systems: a management perspective*. WDL Publications, Ottawa Canada

**Berry B J L** (1964) Approaches to regional analysis: a synthesis. *Annals of the Association of American Geographers* **54**: 2–11

**Berry J K** (1987) Fundamental operations in computer-assisted map analysis *International Journal of Geographical Information Systems* **1**: 119–36

**Berry J K** (1991) GIS in island resource planning: a case study in map analysis. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 285–95, Vol 2

**Burrough P A** (1986) *Principles of Geographic Information Systems for Land Resources Assessment*. Clarendon, Oxford

**Burrough P A** (1989) Fuzzy mathematical methods for soil survey and land evaluation *Journal of Soil Science* **40**: 477–92

**Chrisman N R** (1987) Efficient digitizing through a combination of appropriate hardware and software for error detection and editing *International Journal of Geographical Information Systems* **1**: 265–77

**Chrisman N R** (1991) The error component in spatial data. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 165–74, Vol 1

**Clark D M, Hastings D A, Kineman J J** (1991) Global databases and their implications for GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 217–31, Vol 2

**Corbett J P** (1979) Topological principles in cartography. *Technical Paper 48*, US Bureau of Census, Suitland (also published in *Proceedings of AUTOCARTO 4* (1975), pp. 22–33 American Congress on Survey and Mapping/ American Society for Photogrammetry, Washington DC)

**Dale P F** (1991) Land information systems. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 85–99, Vol 2

**Dangermond J** (1983) A classification of software components commonly used in geographic information systems. In: Peuquet D J, O'Callaghan J (eds.) *Design and Implementation of Computer Based Geographic Information Systems*. IGU Commission on Geographical Data Sensing and Data Processing, Amherst New York

**Davis F W, Simonett D S** (1991) GIS and remote sensing. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 191–213, Vol 1

**DCDSTF (Digital Cartographic Data Standards Task Force)** (1988) The proposed standard for digital cartographic data. Vol I. *The American Cartographer* **15**: 24–8

**Egenhofer M J, Frank A U** (1987) Object oriented databases: database requirements for GIS. In: Aangeenbrug R T, Schiffman Y M (Eds.) *International Geographic Information Systems (IGIS) Symposium, Arlington, Virginia*, Volume II. NASA, Washington DC, pp. 189–211

**Egenhofer M J, Herring J R** (1991) High-level spatial data structures for GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 227–37, Vol 1

**Feuchtwanger M** (1989) Geographic logical database model requirements. *Proceedings of AUTOCARTO 9.* ACSM/ASPRS, Falls Church Virginia, pp. 599–609.
**Flowerdew R** (1991) Spatial data integration In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 375–87, Vol 1
**Flowerdew R, Green M** (1989) Statistical methods for inference between incompatible zonal systems. In: Goodchild M F, Gopal S (eds.) *Accuracy of Spatial Databases.* Taylor & Francis, London and New York, pp. 239–59
**Flowerdew R, Openshaw S** (1987) A review of the problems of transferring data from one set of areal units to another incompatible set. *Research Report* Volume 4. Lancaster and Newcastle, Northern Regional Research Laboratory
**Freeman J** (1975) The modelling of spatial relations. *Computer Graphics and Image Processing* **4**: 156–71

**Gatrell A C** (1991) Concepts of space and geographical data. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 119–34, Vol 1
**GIS World** (1990) *GIS Technology '90: results of the 1990 GIS World geographic information systems survey.* GIS World, Fort Collins, 16pp.
**Goodchild M F** (1988) Towards an enumeration and classification of GIS functions. In: Aangeenbrug R T, Schiffman Y M (eds.) *International Geographic Information Systems (IGIS) Symposium, Arlington, Virginia.* ASPRS, Falls Church, pp. 67–78
**Goodchild M F** (1991) The technological setting of GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 45–54, Vol 1
**Guptill S C** (1988) A process for evaluating geographic information systems. Technology Exchange Working Group – Technical Report 1. Federal Interagency Coordinating Committee on Digital Cartography. *US Geological Survey Open-File Report 88–105.* USGS, Reston
**Guptill S C** (1989) Evaluating geographic information systems technology. *Photogrammetric Engineering and Remote Sensing* **55** (11): 1583–7
**Guptill S C** (1991) Spatial data exchange and standardization. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 515–30, Vol 1

**Healey R G** (1991) Database management systems. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 251–67, Vol 1

**Jackson M J, Woodsford P A** (1991) GIS data capture hardware and software. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 239–49, Vol 1

**Langran G, Chrisman N R** (1988) A framework for temporal geographic information. *Cartographica* **25** (3): 1–14

**McHarg I L** (1969) *Design with Nature.* Doubleday, New York
**Maguire D J** (1989) *Computers in Geography* Longman, London
**Maguire D J** (1990) A research plan for GIS in the 1990s. In: Foster M J, Shand P J (eds.) *The Association for Geographic Information Yearbook 1990* Taylor & Francis, London, pp. 267–77
**Maguire D J, Raper J F** (1990) An overview of GIS functionality *Proceedings of the Design Models and Functionality Conference.* Midlands Regional Research Laboratory, Leicester, 10pp
**Maguire D J** (1991) An overview and definition of GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 9–20, Vol 1
**Maling D H** (1991) Coordinate systems and map projections for GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 135–46, Vol 1
**Marble D F, Lauzon J P, MaGranaghan M** (1984) Development of a conceptual model of the digitising process In: Marble D F, Brassel D J, Peuquet D J (eds.) *Proceedings of the 1st International Symposium on Spatial Data Handling.* Universitat Zurich-Irchel, Zurich, pp. 146–71
**Muller J-C** (1991) Generalization of spatial databases. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 457–75, Vol 1

**Openshaw S** (1991) Developing appropriate spatial analysis methods for GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 389–402, Vol 1

**Parry R B, Perkins C R** (1987) *World Mapping Today.* Butterworths, London
**Peuquet D J** (1981a) An examination of the techniques for reformatting digital cartographic data Part 1: the raster-to-vector process. *Cartographica* **18** (1): 34–48
**Peuquet D J** (1981b) An examination of the techniques for reformatting digital cartographic data Part 2: the vector-to-raster process. *Cartographica* **18** (3): 21–33
**Peuquet D J** (1984) A conceptual framework and comparison of spatial data models. *Cartographica* **21**: 66–113

**Rhind D W** (1974) An introduction to the digitising and editing of mapped data. In: Dale P F (ed.) *Automation and Cartography.* British Cartographic Society Special Publication, Volume 1, pp. 50–68
**Rhind D W** (1991) Counting the people: the role of GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.)

*Geographical Information Systems: principles and applications*. Longman, London, pp. 127–37, Vol 2
**Robinove C J** (1986) Principles of logic and the use of digital geographic information systems. *US Geological Survey Circular 977*. USGS, Reston Virginia
**Robinson A H, Sale, R D, Morrison J L, Muehrcke P C** (1984) *Elements of Cartography*, 5th edn. Wiley, New York
**Robinson V B, Miller, R, Klesh L** (1988) Issues in the use of expert systems to manage uncertainty in geographic information systems. In: Aangeenbrug R T, Schiffman, Y M (eds.) *International Geographic Information Systems (IGIS) Symposium, Arlington, Virginia*, NASA, Washington DC, pp. 89–100

**Samet H** (1990) *The Design and Analysis of Spatial Data Structures*. Addison-Wesley, Reading Massachusetts
**Shepherd I D H** (1991) Information integration and GIS. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 337–60, Vol 1
**Sinton D** (1978) The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In: Dutton G (ed.) *Harvard Papers on Geographic Information Systems*, Volume 6. Addison-Wesley, Reading Massachusetts
**Star J, Estes J E** (1990) *An Introduction to Geographic Information Systems*. Prentice Hall, Englewood Cliffs New Jersey
**Stevens S S** (1946) On the theory of scales of measurement. *Science* **103**: 677–80

**Tomlin C D** (1983) A map algebra. *Harvard Computer Graphics Conference 1983*. Harvard University Graduate School of Design Laboratory for Computer Graphics and Spatial Analysis, Cambridge Massachusetts
**Tomlin C D** (1990) *Geographic Information Systems and Cartographic Modelling*. Prentice-Hall, Englewood Cliffs New Jersey
**Tomlin C D** (1991) Cartographic modelling. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 361–74, Vol 1

**Unwin D J** (1981) *Introductory Spatial Analysis*. Methuen, London

**Weibel R, Heller M** (1991) Digital terrain modelling. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications*. Longman, London, pp. 269–97, Vol 1
**Worboys M F, Hearnshaw, H M, Maguire D J** (1990) Object-oriented data modelling for spatial databases *International Journal of Geographical Information Systems* **4**: 369–83