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Editorial

This first issue of Volume 3 contains a mix of theoretical and applied papers. The former are again dominated by considerations of data structures. D. Mark and colleagues first provide an overview of quadtrees in geographical information systems (GIS), with particular reference to linear quadtrees and to interfacing with digital elevation models in grid form. C. Jones takes up the theme of three-dimensional (3D) structures with reference to applications of GIS to geology although here the emphasis is on octrees and voxels. He shows how it might be possible to combine efficient spatial addressing with topologically-coded boundary representations in three dimensions and suggests that a possible solution to the representation of geological boundary models at different scales may be through a hierarchical classification of the vertices of triangulated surface. In his article, he draws on developments in other fields, such as computer-aided design and medical imaging, where 3D modelling is important.

If much work in GIS has been concerned with a two-dimensional world and has ignored the third dimension, the neglect of the time dimension has been even more marked. In a short paper in Volume 2, G. J. Hunter drew attention to the ease with which digital data in electronic form can be destroyed and the importance of retaining non-current data for a variety of purposes, some of which cannot readily be foreseen at the time. This theme is taken up by R. Vrana, who notes that data are frequently both space- and time-specific and that analysis of change may be complicated by changes in the spatial units by which data are held. He considers the time dimension by reference to three prototype land information systems, for, respectively, forest management, land-ownership and land-use planning. He examines various approaches to the handling of temporal data and underlines the importance of addressing the time dimension explicitly in land information systems. Papers currently accepted for forthcoming issues of the journal suggest that this topic will receive further attention in the near future.

The paper by P. Angus-Leppan, on leave in Thailand from the Department of Surveying in the University of New South Wales to help with the Thailand Land Titling Project, is also about land information systems; but rather than describing a computerized system which does not yet exist, it is concerned with laying the sound foundations for such a system. Up-to-date and accurate records of the extent and title of land holdings is a necessary condition for any computerized system and the author identifies the steps taken to secure such records for Thailand. He points out that the whole project will take 20 years from 1985 and that developing a computerized system will be a major thrust of the second phase from 1990. The paper records the immensity of the task, involving over 21 million titles and the preparation of over 100 000 cadastral maps. He identifies the features that have contributed to the success of the project, including appropriate technology, adequate training and dependence on local staff, contrasting this with the 'rush-in, rush-out' syndrome characteristic of much foreign aid. He also notes that, while there are many countries where land information systems are being developed and many more where they are being contemplated, there are very few that are functional. Those contemplating such systems would do well to examine the Thai experience in laying the foundations of such a system.

The second applied paper, by K. Lowell and J. Astroth, is concerned with a very specific application of a GIS in natural resource management, the use of fire to reduce the risk of damaging, uncontrolled fires in the Hercules Glades Wilderness Area in Missouri. Data for the GIS were derived from aerial photographs of the area over a number of years, soil surveys, topographic maps and records of fires. Statistical analysis is used to evaluate areas which the Forest Service proposes to burn and to determine the likely effects of such burns. This paper, too, is concerned with the time dimension, although as snapshots at particular points in time; the records of actual burns were inadequate to identify their extent.

While it would be inappropriate for the journal to devote articles to specific items of commercial hardware and software, comparative studies, made objectively by those with no vested interest in the products, are likely to be useful in terms both of the results and of the methodologies used to evaluate the products. J. Drummond and M. Bosma provide such an evaluation for low-cost scanners (under US\$10 000). The characteristics of 19 such scanners are described, three are examined in terms of their capabilities for capturing data and one is assessed for geometric accuracy for comparison with established accuracies. They urge, in the light of their findings, that the roles of low-cost scanners be evaluated.

Finally, one of us (JTC) must wear a white sheet. When the title of this journal was under discussion before its launch, there was debate whether the term 'geographic' or 'geographical' should be used. Since the latter was standard British usage, that was chosen. Ron Abler noted in his review of the origins of the National Science Foundation's National Center for Geographic Information and Analysis that American scholars deemed 'geographical' as unacceptable because it was British usage; but the pass was then sold on the eastern seaboard of the Atlantic. An influential report to the British Government was entitled 'Handling Geographic Information' and there has since been formed an Association for Geographic Information. In future we will accept both 'geographic' and 'geographical', while saving face by using GIS wherever possible. For the present at least, the title of the journal will remain unchanged. There is much less agreement on both sides of the Atlantic about 'data'; these will remain unashamedly plural.

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A review of quadtree-based strategies for interfacing coverage data with digital elevation models in grid form

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Abstract. Quadrees represent two-dimensional (spatial) data in a way which takes advantage of spatial coherence in the phenomenon being represented. One major advantage of quadrees is that they are very effective for overlay (Boolean) operations; perhaps more important is the fact that quadrees are compatible with digital elevation models in grid form. This paper reviews the use of quadrees in geographical information systems. Attention is focused on linear quadrees and, in particular, on two-dimensional run-encoding, an effective storage structure for quadrees.

1. Introduction

A geographical information system (GIS) may be defined as "a data base system in which most of the data are spatially indexed, and upon which a set of procedures operates in order to answer queries about spatial entities in the data base" (Smith *et al.* 1987, p. 13). As is the case for any computer application, the issue of data structures is a critical one (Peucker and Chrisman 1975). Once a data structure for a GIS has been adopted, it is very difficult to change it; data structures are also a major factor in determining the efficiency with which queries can be answered within a GIS.

Several of the early GIS used a regular square grid data structure for all data (Tomlinson *et al.* 1976) and grid-based systems are still in use. Often, however, such grids will be redundant for coverage data such as soil type or land use, when cells must be small to achieve adequate boundary resolution. In the 1970s, vector-based GIS data structures became common (see Peucker and Chrisman 1975) and such structures now form the basis of most of the major commercial data structures. Vector-based data structures for topographic data (triangulated irregular networks, or TINs) were also developed during the 1970s (Peucker *et al.* 1978). The major advantage of a TIN is that its vector structure is readily integrated into a vector-based GIS for coverage data (Little 1979). However, large volumes of topographic data are available in the form of regular grids (Ellsal and Caruso 1983). Since a change of data structure almost invariably involves loss of information, it may be desirable to keep topographic data in grid form in a GIS for applications in which topography plays a key role.

In most natural resources applications, elevation data (digital elevation models or DEMs) represent an important component, both directly and in the form of derived measures such as slope. Unfortunately, optimal data structures for topographic and for thematic data may not be easily compatible; thus, once a data structure has been fixed

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for one component of a GIS, the choice of a data structure for the other component must consider compatibility as well as effectiveness for the additional phenomena.

Recently, the quadtree has received considerable attention as a data structure for GIS applications (Martin 1982, Peuquet 1982, 1984, Rosenfeld *et al.* 1982, Samet 1982, 1984, Abel 1983, Lauzon 1983, Chen 1984, Mark and Lauzon 1984, Matsuyama *et al.* 1984, Samet *et al.* 1984, Lauzon *et al.* 1985). Quadrees appear to have many advantages for handling coherent ('blocky') spatial data, and are especially good for geographical overlays. As originally defined, quadrees are inefficient for continuous surfaces such as topography. The use of quadrees for DEMs is discussed in detail in §4 of this paper.

In this paper we first review quadrees in general, then linear quadrees in particular and then discuss the implementation of various GIS procedures within a quadtree-based GIS. We then discuss in more detail a strategy for integrating elevation data into a quadtree-based GIS and for handling GIS data over very large areas.

2. Linear quadrees and GIS

2.1. Quadtree definitions and basic concepts

The quadtree is a data structure which is based on the regular decomposition of a square region into quadrants and sub-quadrants (see Samet 1984, for a detailed review of quadtree concepts). The relations between a quadrant and its subdivisions can be represented as edges or links in a graph; clearly, this graph will be a 'tree', that is, a graph with no cycles. More specifically, the graph representation can be characterized as a 'directed' tree, with each link directed from the 'parent' node toward its 'children' (sub-quadrants). This may be termed a 'rooted' tree, rooted at the node representing the entire enclosing square. Each node in the tree has an out-degree (number of incident edges directed away from the node) of 4, except for 'leaf nodes' which are not subdivided further (and hence have an out-degree of 0). The 'depth' of the tree is denoted by n ; this is the number of links in the longest path from the root to any leaf node. Note that n is also a resolution parameter, since if the level-0 nodes, or pixels, are considered to have a side length of 1, the full region has a side length of 2^n ; a node of level L has side length 2^L and represents a quadrant containing 4^L cells.

Each node of the tree corresponds to a sub-quadrant of the region. A polygon can be mapped on to the region by colouring the quadtree for the region (see figure 1). By convention, a node is coloured black if it lies wholly within the polygon, white if wholly outside the polygon and grey otherwise. Clearly, if a quadtree has a black or white node which is larger than a pixel, the branch of the quadtree can be terminated at that node, as all of its descendants must be of the same colour.

To illustrate the quadtree concept, we describe the construction of a quadtree of a soils map. We assume that the soils map exists as a grid cell representation, that is, we begin with an array of square cells each of which has a soil type. The map is assumed to be enclosed by a square region of side length 2^n .

The 'top-down' construction of the quadtree begins by examining the entire image. If it contains only a single soil type, then the process stops and the quadtree is a single node representing the whole image. If, however, the region contains more than one value (soil type), it is divided into four quadrants (level $n-1$ nodes). Each of these quadrants is then examined for uniformity of value and the process is applied recursively until all sub-quadrants are uniform. Note that single cells in a raster image

Figure 1. A simple binary image and its quadtree.

are uniform by definition and, thus, the process must stop at level-0 if not before. Every homogeneous region identified by this process is a leaf node (terminal node) in the quadtree. For blocky images the quadtree typically will have far fewer nodes than there were grid cells in the original image.

Alternatively, a 'bottom-up' quadtree construction may be useful. Appropriate sets of four mutually-adjacent cells can be examined and combined into a node of level 1 if they all have the same value. Then, if four such level-1 nodes are of the same value and form a valid binary partition of the image, they are combined into a level-2 node and so on. This method will lead to the same set of quadtree nodes as the top-down approach.

2.2. Quadtree data structures

The region quadtree is a relatively new concept. Although many quadtree-related concepts were included in the Canada Geographic Information System (CGIS) in the mid-1960s (Morton 1966, Tomlinson *et al.* 1976), the quadtree idea was first suggested in 1971 (Klinger 1971) and fully developed for the first time in 1976 (Klinger and Dyer 1976). Several data structures for quadtrees have been proposed. One class of structures

explicitly represents all internal (grey) and terminal (leaf) nodes of the quadtree, with nodes linked to parents and children by pointers (Klinger and Dyer 1976, Hunter 1978, Hunter and Steiglitz 1979, Rosenfeld and Samet 1979). Others implicitly represent relations among nodes by their positions within a string of nodes (LaBonte 1977, Kawaguchi *et al.* 1983, Oliver and Wiseman 1983). Another class of data structures represents only leaf nodes, with nodes identified by numeric keys; such representations are termed linear quadtrees (Mark and Abel 1985, Samet and Tamminen 1985). The form of these keys permits topological and spatial relations to be determined from the key values. The data structure is conceptually then a list of the leaf nodes in sequence by key (Gargantini 1982 a, b, Abel 1984).

Several space-efficient forms of linear quadtrees have been reported in the literature. Gargantini (1982 a, b) and Abel (1984) represent explicitly only the black nodes of the tree, inferring white nodes when required. Lauzon (1983) and Lauzon *et al.* (1985) proposed a run-encoding scheme in which runs of nodes of the same colour and consecutive in key sequence were represented by the last key within the run. This is discussed in the next section.

2.3. Two-dimensional run-encoding

Two-dimensional run-encoding (2DRE) is an approach for the compact representation and manipulation of linear quadtrees (Lauzon 1983, Mark and Lauzon 1984, Lauzon *et al.* 1985). A 2DRE file can be constructed by run-encoding a linear quadtree, that is, by combining runs of consecutive leaves of the same value (colour) into single data elements.

Two-dimensional run-encoding exhibits several desirable features for a data structure for use in geographical data processing; for example, multiple attribute encoding, random access and error recovery. This enhances the performance of GIS

8	128	129	132	133	144	145	148	149	192
7	42	43	46	47	58	59	62	63	106
6	40	41	44	45	56	57	60	61	104
5	34	35	38	39	50	51	54	55	98
4	32	33	36	37	48	49	52	53	96
3	10	11	14	15	26	27	30	31	74
2	8	9	12	13	24	25	28	29	72
1	2	3	6	7	18	19	22	23	66
0	0	1	4	5	16	17	20	21	64
	0	1	2	3	4	5	6	7	8

Figure 2. Morton numbers for the first 64 cells of an image and the neighbouring cells.

procedures such as search and overlay, and results in greater storage efficiency and flexibility for the processing of geographical information than do other quadtree structures.

Many linear quadtree systems, including 2DRE, order quadtree records in what is now known as Morton sequencing (figure 2). This numbering sequence was developed by Morton (1966) for use in frame referencing within a large database maintained by the CGIS (Morton 1966, Tomlinson *et al.* 1976, Comeau 1981). Morton sequencing need not be restricted to the exact form introduced by Morton, but can be any one of eight possible combinations of origin location and axis order (see Lauzon *et al.* 1985).

In GIS applications, input data are often in the form of digitized polygon outlines. Mark and Abel (1985) developed an algorithm for producing a 2DRE file directly from a vector representation of a polygon. In remote sensing and other image-based analyses, construction of a 2DRE quadtree is more straightforward. If the image is available for random access, it is not necessary to determine quadtree leaves; rather, one can simply process the image file pixel by pixel in Morton sequence and write a record containing the previous Morton number and attribute code each time the attribute code changes. If data must be processed raster by raster, algorithms for raster-to-quadtree conversion, reviewed by Mark (1986a), can be employed.

The space-efficiency of quadtrees has been reviewed by Dyer (1982), Mark and Lauzon (1985b) and Lauzon *et al.* (1985) and will only be summarized here. For eight digital images, Mark and Lauzon (1985b) found that 2DRE files invariably required less storage space than did pointer-based files or 'image-leaves-only' linear quadtree files. There are other quadtree structures which are substantially more space-efficient than 2DRE (LaBonte 1977, Kawaguchi *et al.* 1983) but these require that the file should be processed from the beginning for all tasks; they are also more sensitive to data errors (see the discussion in Mark and Lauzon 1985b).

3. Data types and their representations in a quadtree-based GIS

A GIS will often have to handle data for very large areas. We therefore assume that any quadtree-based GIS will have at least two levels; the higher level(s) will divide the area of interest into patches and the lower level will represent data within patches. In this section, we assume that if the area of interest is too large to handle as a single quadtree, patches must already have been defined. For each patch, a variety of types of data may exist. Four fundamental classes of data, based mainly on their dimensionality, are recognized here. For each patch, several files may exist, each of which contains data of a different type.

3.1. Type 0: point files

Point data would be held as files in which each point was represented by the Morton key of the pixel containing it. Point locations would be reported to the nearest pixel or grid cell and converted to within-patch pixel coordinates. The coordinates would then be combined to form the Morton number (key) of the point. Each record in the key-ordered file would contain the key of the point and its attributes/values. It may be desirable to retain the pixel coordinates as data elements, although these can be obtained from the Morton number algorithmically. If points have a low spatial density, it may be advantageous to represent the points within a 2×2 , 4×4 or higher-level node within the quadtree of the patches.

Points would be held in key-order for ease of interfacing with other types of data and also because several recent papers (Tropf and Hertzog 1981, Abel and Smith 1983, 1984 a, b) have shown that this is an effective data structure for approaching closest point problems and other questions of computational geometry.

3.2. Type 1: line files

It is well known that quadtrees do not handle line data well. We suspect that it may be best to handle geographical line features as vectors or direction codes within patches, as has been implemented within CGIS and the systems described by Cook (1979) and Weber (1979). Note, however, that boundary lines would not be stored as line data; instead, the bounded regions would be stored as coverage files (Type 2, below).

Recently, Ayala *et al.* (1985) have proposed a modified quadtree structure for handling line and polygon data. They introduced a new type of leaf node, called an edge node; such a node is cut by exactly 1 straight line segment and contains no vertices. Rather than a value (colour), edge leaf-nodes contain a pointer to the equation of the line which cuts them. Ayala *et al.* (1985) called this structure a 'non-minimal subdivision quadtree'. It appears to have considerable potential for handling linear features in a quadtree-based GIS. Methods for handling line data in quadtrees have also been developed by Samet and Webber (1985) and Samet *et al.* (1986).

3.3. Type 2: coverage files

Coverage data, such as land use, soils or rock types, can be stored as linear quadtree files. In most, if not all cases, the 2DRE method for file structuring discussed above would be used. Although 2DRE files are usually viewed as compacted linear quadtrees, they can, as noted above, be constructed simply by visiting all the pixels of an image in Morton order and run-encoding the image values. Thus, the Morton numbers form both a basis for subdivision into patches and a link between different data types. Linear quadtrees (2DRE files) of proximal (Theissen) polygons for a set of points in the plane can be constructed directly from the points using a recursive approach (Mark 1987). Similar algorithms can be developed for calculating trading areas for commercial firms and other space-filling coverage data.

3.4. Type 3: surface files

Quadtree representations are efficient when neighbouring cells often have identical values. Good examples would be gridded topographic data (DEMs) and Landsat or other Multispectral Scanner (MSS) satellite imagery. Several quadtree-related approaches for such data have been proposed. One method fits polynomials to regions defined by the quadtree decomposition (Martin 1982, Chen and Tobler 1986, Leifer and Mark 1987). If the fit is sufficiently good, surface variation within the quadrant is represented by the polynomial surface; otherwise the quadrant is subdivided and the fitting procedure is applied recursively. For solid modelling of subsurface geological data, octrees, the three-dimensional equivalent of quadtrees (Gargantini 1982 b), appear to have considerable potential (Kavouras 1985, Kavouras and Masry 1987, Mark and Cebrian 1986). However, they appear to have no advantages (and several disadvantages) for single-valued surfaces such as most topography.

In fact, for topographical and similar single-valued surface data, it is more efficient to store a value for every grid cell. For ease of interfacing with other types of data, the proposed system would use the Morton number (key) of each pixel as a virtual address

for referencing the elevation within a contiguous binary file. Because of the importance of DEM data in many GIS applications, the following section presents details of a strategy for integrating such data into a quadtree-based GIS, and for performing basic DEM analyses and display procedures.

4. Integrating digital elevation models into a quadtree-based GIS

A DEM can be defined as any machine-readable representation of topographic elevation data. DEMs are widely used in a variety of fields, including cartography, engineering, mining, land use planning and military applications. The most common data structure for DEMs is a regular square grid; the geographical space is partitioned into square cells of constant size and an elevation value is associated with each cell. One problem with regular grids is that often they are redundant. The grid size must be sufficiently small to sample the smallest feature of interest in the entire study area and to define the boundaries of larger features to some required level of precision. Then, because a constant cell size is used throughout the area, cells in most of the region will be smaller than needed (i.e., there will be too many cells, increasing storage space).

In an attempt to address this problem, alternative data structures for DEMs have been designed. The most widely used of these is the TIN, which represents the terrain by a triangulation on a set of points chosen to represent the surface (Peucker *et al.* 1978). However, devices to produce very dense regular grids directly from aerial photographs are now available (Noma and Spencer 1978, Swann *et al.* 1978, Allam 1978). Since grid-to-TIN conversion (Fowler and Little 1979) involves some loss of information, it is desirable to explore grid-based data structures further. Quadrees provide a useful framework for interfacing grid DEMs with coverage data.

The quadtree holds considerable potential here, since it is a grid-based structure which nevertheless has variable resolution. In many ways, the quadtree approach is closely related to progressive sampling (Makarovic 1973, 1979). There is, however, a major problem with the strict application of quadtree concepts to topographical data; it is unusual to find sets of four mutually-adjacent cells which are of identical height. Of course, this depends on the height resolution of the data, but a typical case is the DEM data distributed by the U.S. Geological Survey. These data sets report elevations of 30 m $\times$ 30 m cells as integers in metres (Elassal and Caruso 1983). Ground slope has to be less than 3 per cent before adjacent points will have the same value.

In the quadtree-based GIS developed at the University of Maryland (Samet *et al.* 1984, 1986) and at the University of California at Santa Barbara (Pauquet 1984), topographic data have been included by classifying the DEM data and producing quadrees of the resulting coverage files. Both of the above systems have included only maps of inter-contour areas presented as quadtree files in their published examples. Thus, the topographic component consists of as many binary quadrees as there are inter-contour areas. We assume that slope data would be included in these systems in a similar way, as quadrees of images of classified slope maps.

Incorporation of such secondary data into a GIS is undesirable because the transformations inherent in slope or elevation mapping involve information loss and new user queries may require different class intervals. Thus, if quadrees are to be used in natural resources and related applications, it is essential that we should develop strategies for efficient integration of DEM data into the quadtree environment. We have proposed (Lauzon 1983, Mark and Lauzon 1984, Cebrian *et al.* 1985, Lauzon

et al. 1985) the representation of topography as precisely as possible within a GIS; classified images could then be derived to fit the user's exact requirements.

The proposed solution involves the storing of all cells in the DEM grid; however, the grid is not stored row by row, but rather, the grid cells are stored in Morton sequence. Lauzon (1983) and Lauzon *et al.* (1985) have proposed that DEMs and other full matrix data should be integrated into the linear quadtree GIS by using the Morton numbers as addresses for cell elevation data in a one-dimensional array or file. The use of the Morton key as a position within the DEM file permits easy and efficient integration of DEM data into a GIS based on a linear quadtree structure such as 2DRE. The DEM is not stored as a quadtree *per se*, but rather as a grid arranged in a sequence which is highly compatible with linear quadtrees.

DEM display algorithms for grid data can easily be modified to process data in the Morton sequence. Quadtrees of two-dimensional (coverage) data, such as land use or geology, can then be used to select portions of the DEM for analysis or display. The combination of contiguous Morton-ordered elevation files with 2DRE coverage data provides a useful way to 'window' a DEM according to thematic attribute data. In a 2DRE file of coverage data of a given type, two records with Morton numbers K_1 and K_2 ($K_1 < K_2$) and associated values V_1 and V_2 define a homogeneous region of value V_2 which includes all pixels with Morton numbers from $K_1 + 1$ to K_2 , inclusive. Mark and Abel (1985) have shown that any region thus defined forms either a single 4-connected region or two such regions. A program can retrieve the heights of all points which are on, say, a certain soil type simply by reading the soil type file and examining the soil value. If V_i corresponds to the type (value) being examined, the program can read the heights of all points with keys from $K_{i-1} + 1$ to K_i , inclusive.

5. Summary

Quadtrees are very well-suited to many GIS applications, chiefly because they represent two-dimensional (spatial) data in a way which takes advantage of spatial coherence in the phenomenon being represented. Whereas most research into quadtrees has been concerned with image data, there has recently been a surge of interest in applying quadtrees to GIS situations. This paper has explored the application of quadtrees to more general geographical data, in the context of GIS. Emphasis was placed on the integration of elevation data into a quadtree-based GIS and on strategies for covering very large areas. Attention was focused on linear quadtrees, and in particular on two-dimensional run-encoding, an effective storage structure for quadtrees.

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