APPROACHES FOR QUADTREE-BASED GEOGRAPHIC INFORMATION SYSTEMS AT CONTINENTAL OR GLOBAL SCALES

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ABSTRACT

Several alternative strategies for defining quadtrees and related recursive tesselations over the sphere are examined as possible bases for a global, quadtree-based geographic information system (GIS). We propose that the UTM coordinate system provides the most appropriate basis for such a GIS. The general structure of such a GIS is described.

INTRODUCTION

Quadtrees are an effective way to store grid-cell based information, including geographic data (Gargantini, 1982; Lauzon, 1983; Abel, 1984; Mark and Lauzon, 1984; Samet and others, 1984; Lauzon and others, in press). Briefly, a quadtree first encloses the area of interest within a square, and subdivides the square into for quadrants. Each quadrant is then recursively subdivided into subquadrants until all subquadrants are uniform with respect to image value, or until some predetermined lower level of resolution is reached. With their variable resolution and natural subdivision into hierarchical patches, quadtrees are ideal for handling very large geographic areas. The papers mentioned above all describe <u>linear</u> quadtrees. In such structures, relations among quadrants (nodes in the tree) are indicated not by pointers but rather by linear key numbers based on an ordered list of the node's ancestors.

Because quadtrees are based on square or rectangular grid cells, difficulties may be encountered when the concept is applied to large areas of the Earth's surface (continental scale or larger), since squares cannot tesselate a sphere. The purpose of this paper is to review previous work on this subject, and then to outline a proposed GIS system based on the Universal Transverse Mercator (UTM) coordinate system.

PREVIOUS WORK ON HIERARCHICAL PARTITIONING SYSTEMS FOR LARGE AREAS

<u>Quadrangle-based Systems</u>

One class of solutions to the problem involves partitioning the globe into areas which may be termed <u>quadrangles</u>, cells which are 'square' in latitude-longitude terms. Such systems have a variety of analysis and display problems, since cells are not geometrically square, and furthermore change size and shape with latitude. However, the frequent use of latitude-longitude quadrangles for non-computerized mapping makes them attractive, since printed maps are often used as a primary data source for GIS. Two such systems are reviewed briefly below.

Canada Geographic Information System and Related Structures. A good example of a quadrangle-based GIS which is hierarchical in the quadtree sense (but only down to a certain scale) is the Canada Geographic Information System (Tomlinson and others, 1976; Comeau, 1981). The Canada Geographic Information System was the first full geographic information system. Interestingly, it used what are now seen as quadtree concepts a decade before quadtrees were formally developed as a data structure.

A coordinate reference system suitable for the project had to meet the following criteria (Comeau, 1981, p.2):

1) the system had to accomodate storage of a vast amount of mapped data covering all parts of Canada;

2) the system had to allow for a multitude of mapping scales, without loss of accuracy or the storage of redundant points;

3) the area and shape of the input regions had to be preserved; and

4) the system had to facilitate map to map processing and allow for retrieval of entire regions within the country.

The resulting design was a frame referencing system which allowed for frames of variable size so that the variable scale requirement was met. The storage sequence for the frames on sequential magnetic tape was developed by G.M. Morton and is fully explained in Morton (1966). Each frame is assigned a location key which maximizes the likelihood that its geographic neighbors are also its neighbors on magnetic tape. If each frame is given x (column) and y (row) coordinates, numbered from zero, then the Morton key of the frame can be obtained simply by interleaving the bits of the coordinates (see Morton, 1966; also Lauzon, 1983; Lauzon and others, in press). Within each frame, the hierarchical system is abandoned; data are stored as points and lines, with lines being represented by direction codes (see Tomlinson and others, 1976, p.50-55). Similar 'tiling' systems for geographic information systems are described by Cook (1979) and Weber (1979).

TOPOG. TOPOG is an example of a worldwide topographic data base which uses the quadrangle approach. This system was developed by the U.S. National Telecommunications and Information Administration (Department of Commerce; see Spies and Paulson, 1981). While TOPOG is not a quadtree system, it has many similarities to one.

TOPOG is a hierarchical system. The globe is divided into 36 TOPOG zones, each 5° of latitude in extent. These zones are then subdivided into a total 3060 units termed TOPOG regions. TOPOG regions are 3° of longitude wide between

50^{o} south and 50^{o} north latitude, but are wider (in longitude degrees) toward the poles. Each TOPOG region is then subdivided into 15 TOPOG districts, in a 3 (east-west) by 5 (north-south) pattern. Note that in the mid-latitudes and tropics, these districts are 1^{o} by 1^{o} quadrangles. Next, each district is subdivided into 64 TOPOG blocks, as an 8 by 8 array of quadrangles. For the 48 contiguous states, as well as other mid-latitude and tropical areas, TOPOG blocks are identical to 7 1/2 minute quadrangles. The lowest level of the TOPOG system defines an array of 151 by 151 TOPOG points within each block. For the area between 50^{o} north and south latitudes, these points are 3 seconds apart in both latitude and longitude. Elevations are stored for these points as integer meters above an arbitrary local datum selected to minimize storage requirements and stored at a higher level in the data structure.

In their introduction, Spies and Paulson (1981, p. 3-7) review some alternative terrain storage methods, but did not consider quadtrees, which were not well-known in the GIS and computer mapping literature when their report was being written. Although TOPOG is hierarchical, the hierarchy is irregular, with only one step (districts to blocks) being a power of two (8 by 8). Unfortunately, TOPOG thus missed the possibility of incorporating many of the advances in quadtree handling developed over the last 5 or so years.

Summary of quadrangle-based systems. Both the TOPOG system and CGIS partition the globe into quadrangles. In CGIS, the hierarchical arrangement is one of binary partition, that is, at each step, a cell is split into four quadrants. However, CGIS and the related systems described above partition the region down to some fairly large cell size, and then represent detail in vector form. For a pure quadtree system, the fact that quadrangles are neither square nor of equal size would cause problems for display. In the TOPOG system, partitioning continues down to indivisible grid cells, but the hierarchy is neither binary nor even regular. The problems associated with non-square cells are present, and the potential advantages of quadtree partitions are not available.

Polyhedral Systems

A second class of solutions represents the globe at the most generalized level as a simple polyhedron with triangular faces (a tetrahedron, octahedron, or icosahedron), and then hierarchically decomposes each triangular face into sub-faces (again, a tree, often of out-degree four). A coordinate notation for such a system begining with a tetrahedron was published more than a decade ago by Wickman (1973). Dutton's (1983, 1984) GEM system (Geodesic Elevation Model) begins with an octahedron. At each step in the hierarchy, each triangle is divided into nine faces. Elevation data can be stored in internal nodes of the tree as well as in leaf nodes, leading to efficient generalization. Polyhedral systems are highly appropriate for modelling the Earth and other planetary bodies as solids; their advantages over other methods for mapping on the Earth's surface are less obvious.

Systems Based on Map Projections

The third class of solutions maps the globe onto a plane or set of planes, using some map projection, and then defines a grid cell network in cartesian coordinates on the plane(s). Since no map projection can be both equal-area and conformal, square cells on the map would represent areas in the real world which vary in size, shape, or both. Smyth Associates (1983) developed their own projection, mapping the Earth onto six squares which form a cube; quadtree decompositions were then applied to the faces of the cube. Since equations for map projections can easily be implemented on computers, and since the resulting cartesian coordinate space can be treated as a Euclidean plane for the quadtree, we believe that map projections systems are the most useful basis for a global quadtree-based GIS.

THE PROPOSED GLOBAL QUADTREE SYSTEM

System Overview

This section outlines a continental or world-wide scale GIS based on quadtree concepts and the Universal Transverse Mercator (UTM) coordinate system. In the proposed system, three hierarchical levels are used. The highest divides the world into UTM zones and subzones. Each UTM subzone is then divided into square patches, which are numbered according to the Morton sequence described above. Finally, within each patch, a 256 by 256 array of cells is the basis for the quadtrees or other geographic data files.

For each patch, a variety of types of data may exist. We propose to recognize four fundamental classes of data: points, lines, regions (coverage data), and surfaces. The highest level of the GIS would consist of a data base management system (DBMS) which would contain a directory of patches, data types, and data sets actually available, with summary statistics relating to the file contents. In fact, the _patches_ can be treated as pixels, and summary statistics can be mapped at this highly generalized level.

UTM Coordinates

The use of UTM coordinates is recommended because: conversion of geographic (latitude-longitude) coordinates to UTM is well known and computer programs or formulae are readily available; UTM coordinates are in general use by the armed forces of the United States, Canada, the United Kingdom, and other countries; and the U.S. Geological Survey (USGS) distributes digital data either already in UTM coordinates or with coefficient for conversion to UTM contained in the file headers (see Elassal and Caruso, 1983; Allder and Elassal, 1984).

The UTM system divides the globe into 60 _UTM zones_, each 6 degrees wide (east-west), which extend from 84 degrees north latitude to 80 degrees south, and are numbered from 1 to 60 eastward from the 180th meridian (see Figure 1).

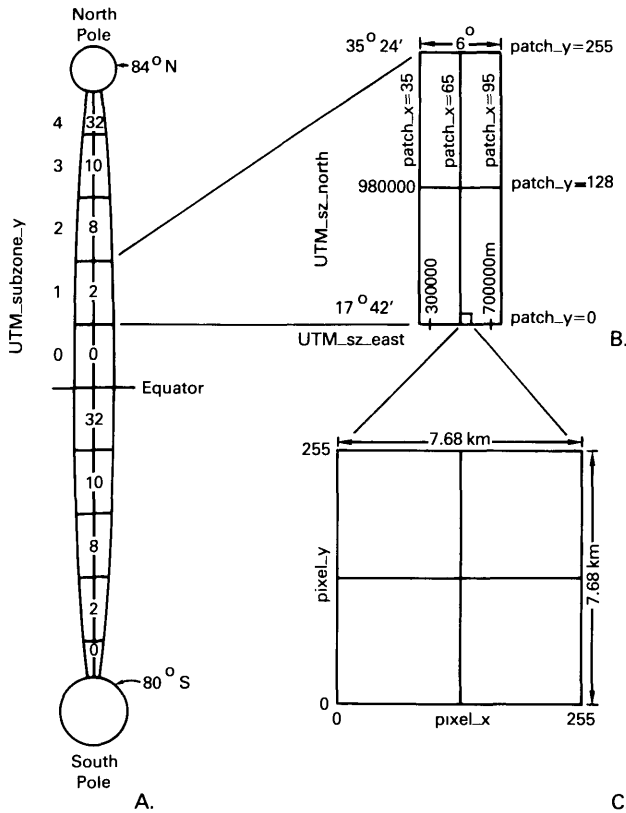

Figure 1: Relations among UTM zones (A), subzones (B), and patches (C), as well as pixels and coordinates from the proposed quadtree-based GIS.

Additional special UPS (Universal Polar Stereographic) zones are used to cover the polar regions. UTM coordinates are given in meters, and are unique within each zone. The central meridian of each zone is given an arbitrary east coordinate ('easting') of 500,000 meters; the equator is the zero point for north coordinates in the northern hemisphere, and is given an arbitrary value of 10 million meters for southern hemisphere 'northings'. It is important to note that the cartesian coordinate systems of adjacent zones are not alligned, except at the equator.

For the proposed system, a standard grid cell size (SGCS), in meters, must be established. Within each subzone, UTM_cell coordinates are obtained by dividing the UTM coordinates by the SGCS. For convenience of processing on a 16-bit processor, UTM_cell coordinates are represented by 16-bit unsigned integers. For the cell sizes anticipated, the north-south UTM_cell coordinate will often be greater than 65536 (2^{16}); we thus propose to divide the UTM zone into <u>subzones</u>. UTM subzone numbers are obtained by dividing the UTM coordinates by (65536 * SGCG), with truncation; then, the UTM_cell coordinates are (UTM / SGCG) modulo 65536. These UTM_cell coordinates are then split into two parts. The upper 8 bits define the <u>patch</u> x and y coordinates. These can be obtained by dividing the UTM_cell coordinates by 256, with truncation. Patch x and y coordinates are then combined into a <u>Morton number</u> for the patch (Tomlinson and others, 1976; Comeau, 1981; Lauzon, 1983; Lauzon and others, in press; see also above). Within each patch, individual cells or pixels are defined in <u>pixel coordinates</u>. Pixel coordinates are obtained from UTM_cell coordinates by taking the UTM_cell x or y modulo 256. Within-patch pixel coordinates may be combined to form a Morton number of the pixel. Figure 2 illustrates the relations among the patch and pixel coordinates and Morton numbers. Direct conversion of UTM_cell coordinates to patch_number and pixel_number can be readily accomplished in a computer language such C, in which individual bits can be addressed through the use of structures. Eventually, such procedure would probably be performed by specially designed chips.

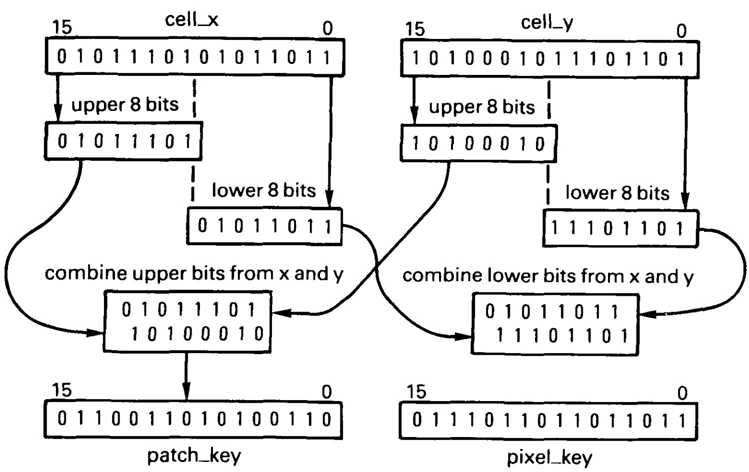

Figure 2: Relationships among the patch and pixel coordinates and Morton numbers, with emphasis on these at the bit level.

Given the UTM zone and UTM coordinates of a point, the following equations are used; for the proposed system for the United States, SGCS = 30 meters (see below):

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UTM_subzone_x = floor (UTM_east / (65536*SGCS));

UTM_subzone_y = floor (UTM_north / (65536*SGCS));

UTM_subzone   = morton (UTM_subzone_x,UTM_subzone_y);

UTM_sz_north  = UTM_north modulo (65536*SGCS);

UTM_sz_east   = UTM_east modulo (65536*SGCS);

UTM_cell_x    = UTM_sz_east/SGCS;

UTM_cell_y    = UTM_sz_north/SGCS;

patch_x       = floor (UTM_cell_x / 256);

patch_y       = floor (UTM_cell_y / 256);

patch_number  = morton (patch_x,patch_y);

pixel_x       = UTM_cell_x modulo 256;

pixel_y       = UTM_cell_y modulo 256;

pixel_number  = morton (pixel_x,pixel_y);
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Any square patch in the world of size SGCS by SGCS is uniquely denoted by three or four numbers: the UTM_zone number (plus UTM_subzone if necessary, depending on the cell size), the patch_number, and the pixel_number.

Implementation for the United States

The U.S. Geological Survey is a major producer of digital cartographic data, an important element in a geographic information system. The USGS currently distributes two classes of cartographic products: Digital Line Graphs (DLGs; see Allder and Elassal, 1984)) and Digital Elevation Models (DEMs; see Elassal and Caruso, 1983). The former contain information on non-topographic line work from USGS 7 1/2 minute quadrangles; locations are presented in arbitrary cartesian coordinates, with coefficients contained in the file header which allow for conversion to Universal Transverse Mercator (UTM) or to State Plane coordinates. The DEMs are presented as regular square grids. Grid cells are 30 by 30 meters, and are alligned with the UTM coordinate system. It is therefore proposed that for the United States, an SGCS value of 30 meters be used.

Section Summary

In summary, three hierarchical levels are used. The highest divides the world into UTM zones and subzones. For the 30 meter cell implementation, each UTM subzone is divided into square patches of side-length 7680 meters (30 x 256), which are numbered according to the Morton sequence. Finally, within each patch, pixels are numbered in the Morton sequence.

DATA TYPES

For each patch, a variety of types of data may exist. It is proposed to recognize four fundamental classes of data, based mainly on their dimensionality. For each patch, several files may exist, each containing a different data type.

Type 0: Point Files

Point files would be held by Morton number. Point locations would be reported to the nearest pixel or grid cell (in this application, 30 meters), 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 2x2, 4x4, or higher-level node within the quadtree of the patches. This could be handled fairly readily within the proposed system.

Points would be held in key-order for ease of interfacing with other data types, and also because White (1983) has shown that this is an effective data structure for approaching closest point problems and other computational geometry questions.

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 geographic 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; rather, the bounded regions are stored as coverage files (Type 2, below).

Weber (1979) in fact viewed his structure as a hybrid between vector and grid-based data structures which capitalizes on the advantages of each. Weber suggests working in one data structure, as long as it is 'economic', and transferring to the other structure once it is more 'economic'. The frame referencing is based on a gridded (in fact, quadtree-like) structure, while the details of a map are recorded in vector format.

Type 2: Coverage Files

Coverage data, such as land use, soils, or rock types, will be stored as linear quadtree files. In most if not all cases, two-dimensional run-encoding (2DRE) will be used as the file structure. This structure, developed by Lauzon (1983) and Lauzon and others (in press), run-encodes a linear (key-based) quadtree file. 2DRE files are an efficient way to store quadtrees, especially for GIS applications, such as overlay (Lauzon, 1983; Mark and

Lauzon, 1984; Lauzon and others, in press). Although 2DRE files are usually viewed as compacted linear quadtrees, they can be constructed simply by visiting all the pixels of an image in Morton order, storing the Morton key of the last pixel of a run of consecutive pixels of the same value (color). The Morton numbers thus form both a basis for subdivision into patches and a link between different data types.

Type 3: Surface Files
Quadtree representations are not efficient if neighboring cells seldom have identical values. Good examples would be a topographic surfaces (gridded digital elevation models) and LANDSAT or other MSS satellite imagery. For data such as these, it is more efficient to store a value for every grid cell. For ease of interfacing with other data types, 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. The integration of the topographic component into a quadtree-based GIS is described in detail by Cebrian and others (this conference).

The System: Summary
For each patch (7680 by 7680 meters in this example), any number of files of one or more of the above file types might exist within the GIS. The upper level of the GIS would consist of a data base management system (DBMS), perhaps relational, which would contain a directory of patches, data types, data sets actually available, and summary statistics for each. Many GIS queries could be answered from data contained in this non-spatial data base. The overall strategy for the system is to examine the actual geographic data files only when necessary.

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