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**VECTOR DATA TOPOLOGICAL ENCODING
ERROR HANDLING AND GENERALIZATION**

**BY
Yueming Ren**

Submitted to the Faculty of Graduate Studies in partial
fulfilment of the requirements of Master of Arts in Geography.

Department of Geography
Carleton University
Ottawa, Canada

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of Canada

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Vector Data Topological Encoding

Error Handling and Generalization

Submitted by Yueming Ren

In partial fulfilment of the requirements for
the degree of Master of Arts

A handwritten signature in dark ink, appearing to read "T. A. Milks", written over a horizontal line.

Thesis Supervisor

A handwritten signature in dark ink, appearing to read "A. C. Milks", written over a horizontal line.

Chair, Department of Geography

Carleton University

July 22, 1992

ABSTRACT

Vector data topological encoding methods, error handling and generalization are described in this thesis.

In this study, a multiple coordinate system to record topological data is proposed. This coordinate system will provide flexibility for recording topological data and make GIS more accurate and efficient. Whole polygon, arcs with centroid, arcs with left/right and arcs with area list topological encoding methods are evaluated. Arcs with left/right and area list topological encoding methods are recommended for future use.

Polygon numbering errors, arc with area list errors, arc direction errors and overlay errors are researched in terms of the causation and correction.

Objective numerical generalization is introduced to improve line generalization. A river generalization system is established based on the nature of river network and previously existing line generalization algorithms. Two river data structures are proposed - a river by river structure and a nodes and segments structure.

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Chapter I. INTRODUCTION

1.1. Maps and Geography

At the core of geography is Cartography -- map making and map analysis. Cartography requires data on position of feature or areas, attributes, and the concept of generalization. This thesis will be concerned with position and generalization as implemented in contemporary automated mapping and analysis activities associated with powerful geographical information system (GIS) concepts and principles.

1.2 Geographic information system overview

Geographic Information System (GIS) is applied to geographically oriented computer technology, integrated systems (Maguire 1991). GIS is a system for capturing, storing, checking, manipulating, analyzing and displaying data which are spatially referenced to Earth (Department of the Environment, 1987).

During the 1960s computer technology became mature. Computers were gradually accepted by many disciplines. More geographic data needed integration for resource assessment, land evaluation and planning. Time and costs of map making needed to be evaluated. Computer mapping was experimented with and conducted in some universities. Fisher's program SYMAP was started in late 1963 (Coppock and Rhind, 1991). It is widely considered as a pioneer computer mapping program. The SYnagraphic MAPping system includes a set of modules for manipulating data to produce choropleth or isoline interpolations and allows the results to be displayed in many ways using the over printing capability of lighter characters to produce suitable grey scales. In Canada, the Canada Geographic Information System was developed in the late 1960s and became the first GIS

in practical use. In the United Kingdom, The Experimental Cartography Unit (ECU) became fully operational in 1967 and started computer assisted mapping activities. In the commercial sector, Environmental System Research Institute (ESRI) was founded in 1969.

The 1970s were the years of lateral diffusion of technology. Technology developments were few, but many more nations, institutions and people became involved in computer mapping. In the early 1970s many cartographers refused to accept the printed product produced by such as SYMAP. For traditional cartography, the new computer technology did not change the fundamental attitude to map making -- the high quality paper map remained the principal data store and end product alike (Burrough, 1987).

While some mapping packages or GISs had topological data structures and modest analytical capabilities in the mid-1970s, these automated cartographic systems had graphic data structures with good graphic editing and plotting capability (Tomlinson, 1980). By the late 1970s, there had been considerable investment for various mapping applications. (Marble et al, 1981). GIMMS was developed by Waugh in 1971. It had good capabilities in mapping but limited capabilities in data manipulation.

More sophisticated data base management systems were introduced into mapping systems in the 1980s. GISs can handle large volumes of data and manipulate or analyze these data. GIS functions included not only map making but also handling and storage of spatial data. Mapping functions became only part of GIS. At the output step, high quality maps or graphic products were produced. Cartographers began to accept these packages or systems. In 1984, Arc/Info version 2.0 became a popular system. In 1986, Version 3.0 appeared. Now some companies and universities are using Arc/Info version 6.0 routinely.

Computer mapping software developed rapidly over these two decades. From Harvard's first mapping package SYMAP developed in 1960s, now there are several thousands of mapping packages in the world (Tomlinson, 1987). Some of these mapping packages have good capabilities in representing spatial data. But a common weak point is lack of spatial data analysis and manipulation. GISs try to combine spatial data analysis, spatial data manipulation and computer mapping together. Many GISs have different modules to meet different requirements. Built-in data base management and extended data base management systems exist in current GISs. Vector data structures are sophisticated and efficient. Traditional map making processes are used only minimally and map draftspersons become unemployed or are retrained.

By the late 1980s, GIS have become widely accepted in North America (Coppock and Rhind, 1991). Central, regional, state and local governments are increasingly involved, as are those in retailing and service delivery (Beaumont, 1991). The National Center for Geographic Information Science Foundation was founded in 1987 (Morrison 1991). GISs have been applied in many fields that we could not imagine five years ago. These fields include police departments, business marketing, sales, store location, fire department, oil spill cleaning and modern warfare etc.

1.3. Objective of the study

Although GIS have been applied in many disciplines, there are some technical aspects still need improvements. This thesis will concentrate on GIS technical aspect.

Polygon boundaries can be represented as lines (or arcs). These lines can be represented as sequences of very short, straight segments which in turn can be represented

by ordered sequences of points. Thus, digital representation of line and polygon information generally consists of ordered sequences of X-Y coordinate pairs. This format for spatial data, where cartographic entities are translated line for line and point for point into digital form, is defined as the vector data structure. All the points recorded in digital form require some kind of coordinate system. Most GISs only have one coordinate system to do all the work. These lack efficiency in terms of data storage and processing. An efficient coordinate system has been demanded: a multiple coordinate system is studied in this research.

Vector data topological encoding is an interesting topic in GIS. Some coding methods have existed for a long time. But many GISs still use inefficient coding methods and lack many features. For instance, some of them lack capabilities to deal with island topology. There is no complete research on current topological encoding status. One objective of this research is to explore and evaluate current topological encoding methods especially on island coding.

GIS vector data preparation can take up to half the time of the whole project. Many GIS users become frustrated about the data, yet vector data is very critical to GIS. Sometimes one point error can cause a GIS to hang. If the vector data file represents area information, this vector data needs clear topological information. Topological coding inconsistencies and topological data errors are the most common vector data errors in GIS. This type of error is not easy to find and correct. Little research has been conducted in this field. Part of this thesis will explore some issues in the nature of vector data errors and error correction.

Although significant advances have been made regarding line smoothing and generalization in the past decade, (fifteen line generalization algorithms have been reviewed

by McMaster (1987), Muller (1988) and Brassel (1988)), no author has worked on objective numerical line generalization. All previous research has been based on line geometry rather than on the line's geographic characteristics. Another objective of this thesis is to develop a river generalization system based on the river line characteristics.

The main objective of this study is to make GIS work more reliably and efficient. A multiple coordinate system can record data more accurately. A reliable topological encoding method can eliminate or avoid errors. Objective generalization can avoid introducing new errors and make the system more accurate and useful.

1.4. Thesis structure

The thesis is structured into six chapters, including this introductory chapter, which introduces the study on vector data processing, topological encoding, error handling, generalization and gives a brief review of the study.

Chapter II provides a detailed review of research on vector data topological encoding. It discusses multiple coordinate systems to record digital data, topological coding methods and island topology.

Chapter III provides the result of a study on vector error. This chapter discusses the cartographic data errors, common digital data errors and data topological errors, their cause, and solutions.

Chapter IV introduces the objective numerical generalization concept and reviews all major line generalization and smoothing algorithms.

Chapter V develops a vector generalization system based on river network characteristics and the previous line generalization algorithm.

Chapter VI gives a brief summary of this thesis and areas of future study.

Chapter II. TOPOLOGICAL ENCODINGS IN GIS

The topology of vector data is a key concept in digital data processing. Any GIS requires vector data to be correctly topologically encoded and stored in some coordinate system.

2.1. Vector data coordinate systems

The basic types of entities considered in computer handling of spatial data are points, lines and polygons. All entities existing in earth space can be represented by one of these three forms.

Digital representation of the basic types of spatial entities has been developed in straight forward functions. Point entities pose few major problems since they may be represented as single pairs or triads of digital coordinates. The representation of line and area boundary information is more complicated.

A line can be considered as a group of connected points. A polygon is a group of connected lines.

Each of the spatial entities being considered exists within the bounds of coordinate systems that have been developed over a period of many decades. These coordinate systems provide a means of exactly positioning the entities in earth space and of providing measurements of such attributes as perimeter length, area, distance and direction between entities. It is possible to transform one coordinate system to another system. A map projection is one of these coordinate transformations.

The coordinate system used in a GIS is very important. It will affect GIS data precision, results of analysis and modelling, and output quality. Traditionally a GIS uses one coordinate system to do all geographic analysis, graphics manipulation, and generate output on a video display or printer or plotter. This type of GIS cannot store data efficiently and cannot be used to analyze data effectively. For example UTM projection Y coordinates are greater than 4,000,000 in Canada, while VGA screen Y coordinates are fewer than 480. It is inefficient to use one coordinate system to represent value between 0 and 480 and value larger than 4,000,000. Therefore scaling and generalization problems arise in representing the UTM projection for Canada.

Screen Coordinate Systems:

The simplest coordinate system is the screen system, in which one corner of the display (usually the lower left) corresponds to the origin of the coordinate system. The positive x-axis extends from the origin to the lower right corner of the display, and positive y-axis extends from the origin to the upper left corner of the display. When a GIS displays graphics elements, it must specify distances and locations in pixels normally within the range of a two-bytes integer. There are two fundamental drawbacks for a GIS with this kind of coordinate system:

- (1) The graphics system is device dependent; and
- (2) It is difficult to draw output in convenient absolute units such as centimetres;

The following steps must be followed if GIS screen coordinates are used to draw lines in centimetres:

- (1) determine the width (in centimetres) of the video display or printer paper;

- (2) determine the width (in pixels) of the video display;
- (3) divide the width in pixels by the width in centimetres to determine the ratio of pixels to centimetres;
- (4) Use this ratio to draw a line.

World Coordinate systems:

A world coordinate system is a device independent system. World coordinate units can be projection coordinates, latitude, longitude, or absolute distance measures for reality in miles, kilometres. The precision could be four bytes integers or eight bytes floating points.

Device Coordinate systems:

Device coordinate system units must be in device units such as centimetres, or inches. The reason to separate screen coordinate systems from device coordinate systems is that device coordinates are used for hardcopy output in such peripherals as plotters or printers.

Multiple Coordinate Systems:

A single coordinate system does not provide the flexibility that most GIS applications need. In most applications, GISs draw output on video displays, printers or plotters. Raw geographic data normally are projection coordinates or latitude and longitude coordinates. It is obvious that a single coordinate system is impractical or inefficient.

A multiple coordinate system uses a transformation matrix to define the coordinate system in different stages of GIS processing. A transformation matrix to convert one coordinate system to another is a way to establish a multiple coordinate system. A

transformation matrix can do the following tasks:

- (1) run on a variety of video displays, printers, or plotters;
- (2) use convenient units of measurements (centimetres, inches, etc.);
- (3) scale or shift vector data; and
- (4) rotate vector data.

For any point (x,y) in a source coordinate system, you can decide the corresponding point (x1, y1) in the target system can be determined using the following matrix multiplication:

$$[x \ y \ 1] \times \begin{bmatrix} M11 & M12 & M13 \\ M21 & M22 & M23 \\ M31 & M32 & M33 \end{bmatrix} = [x1 \ y1 \ 1]$$

In the following example, the original point in the source coordinate system is always identical to its corresponding point in the target coordinate system.

$$[x \ y \ 1] \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = [x1 \ y1 \ 1]$$

When scaling a vector by using the scaling transformation, the matrix element M11 contains the horizontal component, and matrix element M22 contains the vertical component:

$$[x \ y \ 1] \times \begin{bmatrix} \text{horz} & 0 & 0 \\ 0 & \text{vert} & 0 \\ 0 & 0 & 1 \end{bmatrix} = [x1 \ y1 \ 1]$$

When rotating a vector clockwise by using the rotation transformation, the matrix element M11 contains the cosine of rotation angle, M12, the negative sine of the rotation angle; M21, the sine of the rotation angle, and M22, the cosine of the rotation angle:

$$\begin{bmatrix} x & y & 1 \end{bmatrix} \times \begin{bmatrix} \cos & -\sin & 0 \\ \sin & \cos & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} x1 & y1 & 1 \end{bmatrix}$$

For a GIS, a well-designed multiple coordinate system is essential. In the digitization process, digitizer table coordinates need to be transformed to projection coordinates. In data processing, vector data need to be stored efficiently in world coordinate system. At the output stage, a screen coordinate system is needed for video display and a device coordinate system is needed (in absolute units) for hardcopy output. The proposed multiple coordinate system and matrix transformation will be useful for GISs.

After selecting suitable coordinate systems, the next step will be the encoding of spatial entities. Several forms of spatial topology will be discussed in the following section of this chapter.

2.2. Topological Concepts in GIS

Topology is a branch of mathematics that investigates the properties of a geometric form that is unaltered if the form is subjected to any one-to-one continuous transformation

(Webster's Dictionary). Geography is dealing with three or two dimensional spaces. It is important to define which aspect in space is related to another. Even in the discrete world of digital data, space is usually represented as a continuum in which places have connections and relationships of various sorts. Geographic relationships may be expressed geometrically and measurements are required to quantify relationships between phenomena made up of points, lines and areas. Topological principles can be applied to describe their relationships. City blocks, streets, and street intersections have mutual topological relationships which can be logically and quantitatively described, which in turn can be used to locate urban phenomena independently of any coordinate system relating to the earth's surface. River tributaries connect in ways which permit their topological ordering and attribute calculation such as mean intermediate angle. Landforms (or topography) also have a topology in which all critical features (peaks, pits, passes, ridges, water courses, hills, and valleys) are tied together, and may be represented as a graph as well as a surface, and they have a topology in terms of length, area, flow, and density, and other parameters intrinsic to the spatial system. It is claimed that no characterization of a region can be considered adequate without references to topological notions of dimensionality, adjacency and connections (Dutton, 1977).

Early cartographic data bases were descriptions of all objects, whether points, lines, or areas, simply and independently. This limited their use to the reproduction of maps and hindered error correction and analysis. When polygons are described as independent lists of vertices, each point on a shared boundary should have at least one duplicate elsewhere in the file. If such a point is added or deleted, its neighbour's description ought to be

similarly modified. But if each polygon is separately described, there is no straight forward way to accomplish this without the explicit encoding of topological information of adjacent and connecting objects which name one another, making it obvious which other objects are affected when a given object is modified. Topological encoding thus yields immediate practical benefits to computer cartography, as well as permitting many different objects and their relationship to be described systematically in one geographic database.

2.3. Topological Data Coding

Encoding geographic features according to their topological relationship is important in GIS. Encoding can be defined as the assignment of coordinates to data objects.

Encoding can be direct or indirect. Direct coding is the encoding of the object itself, for example, encoding of a point reference for a property, or digitizing the course of a river. Indirect coding is where the encoding is calculated or deduced by using some links between the objects and an external base, usually an external geographic database.

Waugh (1976) described five different encoding methods, which reflect basic geometric principles.

(1) Index encoding is often used as a basis for indirect encoding. There is no spatial link between objects. For example, post codes (zip codes) are one common form of index encoding;

(2) Grid encoding is encoding grid cells and information on these grid cells. The occurrence of the encoding depends on the cell size;

(3) Point encoding has the same principle as grid encoding, but point encoding ensures all objects are unique. Point encoding can always be aggregated to grid form;

(4) Boundary encoding uses one line to form a polygon. (ATLAS and GIMMS are examples of boundary encoding GIS);

(5) Segment encoding is a description of the segment make up of a network. The network is composed of nodes, segments and areas. Segment encoding methods have extensive links that the system generates, which can be machine checked by using topological editing procedures.

Fifteen years passed and some of Waugh's geometric encoding rules are not used any more. Now four different kinds of encoding methods are used in the GIS software which represents spatial information:

(1). Whole polygon encoding

Whole polygon encoding is the same as boundary encoding, described by Waugh (1976). The start point is the same as the end point. Every polygon is a unique unit in the coding. Most GIS users now call polygon encoding non-topological coding. Adjacent polygons have common boundaries.

The advantage of whole polygon coding is that it is easy to search and retrieve, easy to shade or label a polygon and easy to program. The disadvantages are inefficient data storage, difficulty in editing, longer time processing, difficulty in digitizing, difficult in polygon creation and poor in output quality (e.g., common boundary double plotting).

Many GIS and mapping packages still use polygon encoding; ATLAS*GIS, ATLAS*GRAPHICS, MapInfo, GIMMS, Map Collection. Other high end packages such as

Arc/Info still support polygon encoding.

(2) Arcs with centroid encoding

Every polygon must have one centroid only. GIS software creates topological relationship from arcs and centroid.

The advantages of this encoding method are that digitizing is simple, storage is efficient, data editing is easy, connecting attribute data is simple and output is high quality.

The disadvantage are that points in polygon calculation and error checking and handling are difficult.

Some GIS packages, such as Micro Station support this encoding.

(3) Arcs with area list encoding

This encoding method uses arcs and nodes and their topological relationship. Every polygon is described by an arc number and its direction. GIS software reads the polygon first to find which arcs belong to which polygon and then the software creates an internal topology.

This encoding method has the same advantage as arcs with centroid encoding. DLG (USGS Digital Line Graph) format is a typical example of this encoding.

Arc/Info uses this encoding as basic data organization.

(4). Arcs with left/right topology

This uses encoding of arcs and their left/right relationship to create polygons. Every arc is assigned a left and a right polygon number. GIS software reads the arcs, finds the

left and right polygon numbers, then creates a topology based on these left/right relationships.

This encoding method has the same advantage as arcs, nodes and points encoding.

TIGER file (Topological Integrated Geographic Encoding and Referencing, US Census Bureau) data use a typical left/right topology encoding system.

Many systems, such as Arc/Info, can support TIGER data.

The following part will use a coordinate system to illustrate above topological encoding methods.

2.4. Examples of Four Different Encoding Methods.

Four of the encoding methods outlined above are developed using a coordinate system.

1. Whole polygon encoding

polygon 1: (2,2), (2,1), (1,1), (1,2), (2,2)

polygon 2: (2,2), (3,2), (3,1), (2,1), (2,2)

2. Arcs with centroid encoding

arc 1 (2,1), (1,1), (1,2), (2,2)

arc 2 (2,2), (2,1)

arc 3 (2,2), (3,2), (3,1), (2,1)

centroid (1.5, 1.5) (2.5, 1.5)

3. Arcs with area list topology

Nodes (2,2), (2,1)

arc 1 (2,1), (1,1), (1,2), (2,2)

arc 2 (2,2), (2,1)

arc 3 (2,2), (3,2), (3,1), (2,1)

area 1 containing arc 1,2

area 2 containing arc 2,3

4. Arcs and left/right topology

arc 1 left area 0 right area 1

arc 2 left area 2 right area 1

arc 3 left area 0 right area 2

Arcs with left/right and arcs with area list topological encoding method which have clear topological link, are simple to process data and are widely used. Therefore they are recommended in the future implementation.

The above four encoding methods are widely used in current GISs. But the most difficult part in topological encoding is island coding. There is great confusion existing in island topology. The following section will concentrate on island topology encoding.

2.5. Island Topology

Islands are features such as lakes in a base map. Topology creation for islands is more complicated than that for adjacent polygons. Some special situations such as islands contain other islands which make island topology creation more fascinating.

The following discussion is based on two basic topological encoding methods: polygon encoding, and segment encoding (consisting of arc with centroid topology, arc with area list topology and arcs with left/right topology).

1 Polygon encoding

Four polygon encoding methods for island topology can be identified.

METHOD A:

Figure 2.1. illustrates one kind of island topology coding method. The envelop polygon start point will be duplicated several times during encoding. Every duplicate start point indicates that an island follows in the coding. After initial envelop polygon encoding, each individual island will be encoded in a polygon format. Island polygon points will be recorded in both the envelop polygon and island polygon coding.

Envelop polygon 1: point 0, 1, 2, 3, 0, 10, 11, 12, 13, 14, 15, 10, 0, 20, 21, 22, 23, 24, 25, 26, 20, 0

Island polygon 10: point 10, 11, 12, 13, 14, 15, 10

Island polygon 20: point 20, 21, 22, 23, 24, 25, 20

This encoding method has following advantages: the topological relationship is clear; and area and centroid calculation is simple for the envelope polygon and individual islands.

Figure 2.1. Polygon topological encoding method A

METHOD B:

Figure 2.2. illustrates a polygon topology creation based on an envelope polygon and connected islands. The difference between this method and previous one is in the initial envelope polygon creation.

Envelop polygon 1: Point 0,1,2,3,0, 10,11,12,13,14,15,10, 20,21,22,23,24,25,20, 30,31,32,33,34,35,36,30,0

Polygon 10: 10,11,12,13,14,15,10

polygon 20: 20,21,22,23,24,25,20

polygon 30: 30,31,32,33,34,35,36,30

 

Figure 2.2. Polygon topological encoding method B

METHOD C:

This method (Figure 2.3) is similar to the first method. The only difference is an island in the envelope polygon can be created from any point in the envelope code (not just end or start point). This method is more flexible than method A and method B.

Figure 2.3. Polygon topological encoding method C

Area and centroid calculation are the same as for the first method.

METHOD D:

This method (Figure 2.4) creates an outline polygon first but does not indicate how many islands it contains. It looks like very simple, but this method records a confused topology. It requires calculation from the coordinates to find which island is in which polygon. There are some commercial GIS packages (such as MapInfo) which still use this method. But this method should not be recommended, because of the possible inconsistencies and inefficiencies in encoding an polygon.

Envelop polygon 1: Point 0,1,2,3,0

Polygon 10: 10,11,12,13,14,15,10

polygon 20: 20,21,22,23,24,25,20

Figure 2.4. Polygon topological encoding method D

Among the above four whole polygon encoding methods, first encoding method are acceptable. Area and centroid calculation are simple and topology are clear in the method A encoding method. If a system cannot avoid using whole polygon encoding, the above method A encoding method are suggested.

Figure 2.4 is used to illustrate the following topology encoding methods for islands.

2 Arcs with area list topology

This method records polygon topology which separates the area list from the arc coordinates list.

Arc list:

Arc 1: point 0,1,2,3,0

Arc 2: point 10,11,12,13,14,15,10

Arc 3: point 20,21,22,23,24,25,20

Area 1: has 3 arcs, 1 envelop, 2 included islands

arc: -1 0 -2 0 -3

Area 10: has 1 arc, 0 envelop, 0 included islands

arc: -2

Area 20: has 1 arc, 0 envelop, 0 included islands

arc: -3

3 Arc with left/right topology

This encoding method has only an arc list.

Arc list:

Arc 1: left area 1 right area 0

point 0,1,2,3,0

Arc 2: left area 10 right area 1

point 10,11,12,13,14,15,10

Arc 3: left area 20 right area 1

point 20,21,22,23,24,25,20

4 Arcs with centroid topology

Arc 1: point 0,1,2,3,0

Arc 2: point 10,11,12,13,14,15,10

Arc 3: point 20,21,22,23,24,25,20

Points in polygon:

centroid 100 area 1

centroid 101 area 10

centroid 102 area 20

2.6. Commercial Examples of Topological Encoding

Two examples of commercial GIS encoding procedures are presented.

In the ARC/Info system, for a typical map points, lines and areas are stored as nodes, arcs and polygons. Figure 2.5. illustrates this approach (ESRI 1988), Table 2.1 shows the topology.

Figure 2.5. Example of Topological Relationships Between Arcs, Label points, Nodes, and Polygons

Table 2.1. Topology from Figure 2.5.

Polygon Topology			Node Topology	
User-ID	Poly#	Arc#	Node#	Arc#
11 99	1	1,3,7	1	1,2,3
	2	1,2,4	2	2,4,5
	3	3,5,2, 0,6	3	1,4,7
12	4	5,7,4	4	3,5,7
40	5	6	5	6

Arc Topology				
Arc#	From Node#	To Node#	Left Poly#	Right Poly#
1	1	3	2	1
2	2	1	2	3
3	1	4	1	3
4	2	3	4	2
5	2	4	3	4
6	5	5	3	5
7	3	4	4	1

In preparation for the 1990 census, US Census Bureau developed the TIGER system. TIGER/Line file data originated with either the USGS DLG (Digital Line Graph) data sets or 1980 DIME files. These data sets were merged into a single, seamless data set that is topologically structured. TIGER/Line files use one geographic area (the basic unit is the county) has six related files (later expended to ten files). File 1 represents basic arc information such as arc number, arc start points, arc end points, multiple left/right area numbers (including county, MCD, census tract, census block, zip codes) street name, street address and arc census classification feature codes etc. File 2 represents arc intermediate

coordinates. File 3 and File 4 describe arc alternative feature names. File 5 and File 6 describe the additional address information. File 7-10 contain additional information about point in polygon, address etc. TIGER/Line files contain comprehensive geographic information for individual users to extract information as needed. For example, choropleth mapping requires only TIGER/line file 1 and file 2 to extract arc coordinates, arc topology and to produce the choropleth boundaries.

The TIGER/Line file is a typical arc left/right topological encoding result. All arcs have left area and right area numbering. If an arc is not one of a series of arcs forming an area, the arc left and right area numbering is the same.

According to the Census Bureau the TIGER/Line file data structure is based on the 0-cell, 1-cell, 2-cell ideas, following Marx (1986):

A 0-cell represents only a feature intersection or end point, not intermediate points used to define shape or other types of point location.

A 1-cell represents the line connecting two 0-cells, not the shape of the line.

A 2-cell represents the smallest area formed by a linked set of 1-cells. Collections of 2-cells define geographic areas as small as a census block.

In fact, 0-cell, 1-cell, 2-cell concepts are nodes, arc and areas. The relationship between these cells is the relationship between nodes, arcs, and areas.

TIGER/line data constructs multi-level topological models, for instance, from state to county to census tract and to block.

Table 2.2. shows topological encoding methods in some major commercial GIS software. TIGER as a latest developed topological data system represents arc with left/right topological encoding method. It is clean and efficient. MapInfo, GIMMS and ATLAS*

represent unmaturred GIS using the whole polygon encoding method. Arc/Info and SPANS try to accommodate all available encoding methods and make the system more complicated.

Table 2.2 Topological encoding methods used in commercial systems:

	TIGER	MapInfo	GIMMS	ATLAS*	Arc/Info	SPANS
whole polygon	no	yes	yes	yes	yes	yes
Arc/Centroid	no	no	no	no	yes	yes
Arc/Area list	no	no	no	no	yes	yes
Arc/Left right	yes	no	no	no	yes	yes

Selection of a suitable coordinate systems and topological coding methods are the first step in geographic data processing. Digital data will be recorded only then in a unique coordinate system using a consistent encoding method. But digital data has its own special form. Many errors will be introduced during digital data coding. The next part of the thesis will look into these digital data errors and find a way to correct them.

Chapter III. VECTOR DATA ERROR HANDLING

Error, in a narrow mathematical sense, is the difference between a measured quantity and the true value for the quantity. In a traditional cartographic context, any deviation between the map and the earth surface could be considered as error. For many cartographic objects, however, the true value can never be determined (Muller, 1987). In general, error can be viewed as the combined result of a series of transformations from data capture, data transformation, data manipulation and data display.

Two types of error are considered --- cartographic and digital data error.

3.1. Cartographic data errors

Previous researchers have done some work on general cartographic data error handling. MacEachren (1985) concluded that there are four main factors which influence map error: data collection methods, data classification procedures, symbolization techniques and map production procedures. Morrison (1971) tried to find a connection between errors and their cause. Collection, recording and manipulation error results from machine, instruments and human operators. Muller (1987) discussed five principal components of errors on maps:

- a) Locating ground position error. Although geodetic and trigonometric networks are usually established with very high accuracy, not all points on a map sheet are fully tied to those networks.
- b) Interpreting data from direct field observations and examination of aerial

photograph error.

- c) Generalizing to an appropriate scale error.
- d) Converting the data to map space error. Projection errors, in the form of distances, angles and areas vary continuously over the surface of the map.
- e) Drafting and photomechanical reproduction error.

Burrough (1987) concluded that there are three types of data error (table 3.1.). He tried to find the cause of those problems.

Table 3.1. Sources of possible error in a GIS (Burrough 1987).

- I. Obvious sources error
 - 1. Age of data
 - 2. Areal coverage -- partial or complete
 - 3. Map scale
 - 4. Density of observation
 - 5. Relevance
 - 6. Format
 - 7. Accessibility
 - 8. Cost
- II. Errors resulting from natural variations or from original measurements
 - 9. Positional accuracy
 - 10. Accuracy of content
 - 11. Sources of variation in data
- III. Errors arising through processing
 - 12. Numerical errors in the computer
 - 13. Faults arising through topological analyses
 - 14. Classification and generalization problems.

Digital data not only contain these common cartographic errors, but also contain other special form of error. Topological inconsistency is a major problem in digital data errors.

3.2. Digital data errors

Digital vector data can be digitized from a paper map. Cartographic error could be transferred from the paper material to the digital data base. In the case of manual digitizing, most additional error comes from the operator, since the precision of the digitizer (typically 0.001 inches resolution) exceeds the perceptual and physiological capabilities of a human (Jenks 1981). The quality of vector data will affect the result of geographic information processing. Several researchers have addressed some vector error in digitizing and data transformation. Wolfendale (1967) discussed position accuracy, nature of random errors and machine errors. Jenks (1981) addressed the human psychological and physiological errors. Psychological errors are those which arise from psychomotor problems in line following. The digitizer operator either cannot see the line or cannot move the crosshairs along the line, resulting in the digital line being displaced. Physiological errors are caused by involuntary muscular spasms that tend to parallel the longitudinal axis of the centre line (Jenks 1981). Three such errors are spikes, switchbacks and polygon knots.

Some vector data errors such as spikes and switchbacks are unimportant because they do not affect topology and these errors can be ignored by the computer. Some other errors such as knots must be corrected before topology creation is undertaken by the software. It is important to realize that only clean vector data can be used in a GIS to create vector

topology and to do spatial data analysis.

Figure 3.1. Errors
G - Gap, O - Overshoot, S - Spike and switch back
K - Knots, W - Weird Polygon

Another digital data error is node match error (not matching exactly on same node). If two connected nodes are not "matched", topology creation will fail. It is caused by both computer and digitizer operator. Because of computer screen resolution, it is often difficult to tell if two nodes are matched or not. Nodes match functions are implemented in some systems in digitizing to help the user to match nodes unambiguously. Overshoots (O) or gaps (G) are caused by node match errors (Figure 3.1).

The efficient way to remove an overshoot is to set an overshoot tolerance, and to process nodes one by one to check connection and length of line. If length of line is smaller than the tolerance, this arc will be removed from the data. Similarly a gap tolerance (distances between dangling arcs and destination arcs) is needed in removing a gap. If the distance is smaller than the tolerance, danglers are connected to destination arcs.

Knots are those points which form extra polygon around nodes. They are caused by the digitizer operator who digitized extra points before matching nodes. The efficient way to remove knots is to set a knot tolerance around nodes to remove those extra points.

A "weird" polygon is an extra polygon formed by knots. To find a weird polygon, Burrough (1987) described a full topological polygon network data structure, which can be used to find a weird polygon in a data set. Basically the search checks the accumulative turning angle of all connect arcs which form the principal polygon. If the accumulative turning angle is not 360 degrees, the polygon is "weird" and thus the weird polygon can be traced and corrected.

Line duplication occurs when two lines or parts of lines have the same X-Y coordinates. Line duplication is normally caused by merging two vector data sources, or by digitizing software, or by a data conversion program. To remove a duplicated line requires comparison of all coordinates for all lines in two digitized directions in the file. It requires efficient vector data storage and an efficient algorithm.

Spaghetti lines typically come from a CAD package such as AutoCAD which can be used as a source of geographically referenced spatial data. Normally CAD packages do not have any topological data structure and topological data analysis functions. The only method to correct spaghetti line is to calculate a line intersection.

All the above errors are positional errors. The next part will look into topological errors in digital data.

3.3. Data Topological Inconsistency

The major problem in using digital geographic data is topological inconsistency. It is caused by digitization errors, different data format conversions, or original map boundary errors.

Haralick (1980) described topological consistency demands:

- 1) Every point in the plane should be in some region bounded by a sequence of arcs in the data base;
- 2) There should be no extraneous arcs in the data base;
- 3) Clear neighbourhood relations should be defined between the polygons or arc segments.

Algorithms for topological consistency checks depend on encoding methods. For example, there are two ways to perform topological consistency checks on arc left/right encoding. In the first way, all entities must be searched for all boundaries. In each simple boundary, it must be verified that in its circularly ordered list of arc names, one end point of every arc must match one end point of a successor arc. As each arc in succession is being checked, reference can be made to the relation (arc, left area, right area) to verify that the current region being circled indeed appears to the arc's right when traversing the arc in the directions of the ordered arc sequence bounding the region. In the second way, It requires that a list of arc end points be prepared. In this list, each end point, called a node, must point to all the arcs having it for one of its end points (Burrough 1987).

One of the first attempts to build explicit topological relationships into a geographical data structure was the DIME system of the U.S. Bureau of Census. The records in the DIME system represent segments with associated directions. The topological information

stored makes it possible to automate procedures for checking consistency that will detect errors which may have been introduced during the encoding.

The first full topological polygon network structure was the POLYVRT data structure used to represent the partition of an area into polygons. The basic data entity in this scheme is the chain consisting of straight line boundary segments that have common regions on their left and right sides. A set of chains form a boundary. This system allows automatic checks for weird polygons and dead ends.

Now GIS software can provide more sophisticated topological consistency checks in vector data processing. For example, Arc/Info provides several different ways to check topological inconsistency. It will check duplicate arcs, dangle arcs, overshooting arcs while building the topology from arcs. It automatically checks topological relationships when reading some other data format such as the TIGER (U.S. Census Bureau) data and creates a new error free data file. In some situations, such as duplicate or dangle arcs, Arc/Info ignores these topological inconsistencies and provides new correct topological data.

Some commercial data normally provide topological information for users. For example TIGER data has multiple, hierarchical topology information. But these data always have topological inconsistency problems. It requires GIS software with more flexible capabilities to deal with these inconsistency problems.

Three polygon topological error schemes are described in more detail as follows.

3.3.1. Polygon Topological error 1: left right polygon numbering errors

In some data files, for example TIGER data, topology is based on the left/right polygon numbering. These left/right polygon numbers are based on arc direction, and polygon number. For example Table 3.2 and 3.3 illustrates correct and incorrect left/right topology for Figure 3.2, respectively.

ARCS: 1,2,3,4,5,6,7,8,9,10,11,12
AREAS: 0, 100,101,102,103,104

Figure 3.2. Rectangle area

Table 3.2. Correct left/right topology

arc	direction	left-poly	right-poly
1	+	101	100
2	-	100	102
3	+	103	100
4	+	104	100
5	+	104	101
6	+	102	101
7	+	102	103
8	-	103	104
9	+	0	101
10	+	0	102
11	+	0	103
12	-	104	0

Table 3.3. Incorrect left/right topology

arc	direction	left-poly	right-poly
1	+	101	200
2	-	100	102
3	+	103	100
4	+	104	100
5	+	104	101
6	+	102	101
7	+	102	103
8	-	103	104
9	+	0	101
10	+	0	102
11	+	0	103
12	-	104	0

An error could be detected (Table 3.3) as follows:

The right polygon 200 does not exist adjacent to Arc 1 in this rectangle area (Figure 3.2). One easy way to correct this error is to find all arcs in each area, say area 100 first. If three arcs are traversed from arc 2 to arc 3 to arc 4, then a search to find arc 1 can be made. Because arc 1 also connects to arc 2, arc 1 is also a boundary of polygon

100, and therefore the right polygon number can be automatically connected by an appropriate algorithm.

3.3.2. Polygon Topological error 2: Arc with area list topology error

Reference is again made to Figure 3.2. Correct polygon topology in this scheme is given in Table 3.4. Incorrect topology is shown in table 3.5 in which polygon 100 is missing arc #1 and has an unrelated arc #5.

Table 3.4. Correct Polygon topology

area	containing arcs
0	9, 10,-11, 12,
100	1, -2, 3, 4,
101	1, 5, 6, 9,
102	-2, 6, 7, 10,
103	3, 7, -8,-11,
104	4, 5, -8, 12,

Table 3.5. Polygon topology Error

area	containing arcs
0	9, 10,-11, 12,
100	5, -2, 3, 4,
101	1, 5, 6, 9,
102	-2, 6, 7, 10,
103	3, 7, -8,-11,
104	4, 5, -8, 12,

Polygon 100 missing arc #1
and has extra arc #5.

To correct this kind of topology error, one needs to examine polygon 100 and follow all arcs to find that arc #1 is missing and arc #5 is not related to the polygon, although it shares a node with two of the containing arcs for polygon 100 (i.e., arc 2 and 4). Again, an automated checking algorithm is possible.

3.3.3. Polygon topology error 3: Arc direction error

Another common arc with area list topology error is an arc direction error. These arc directions are easy to confuse especially in dealing with island topology. One Arc/Info island topology error has existed for a long time. It generates wrong direction signs for an island.

3.4. Overlay error

Additional errors result from a frequent process in GIS analysis --- map overlays.

An overlay analysis of four layers, with each map 85 percent accurate for classification, could produce a composite map with an average accuracy of less than 52 percent. That is, the resulting map from the overlay analysis is less accurate than the accuracy of the least accurate layer used. These inaccuracies arise from three error sources -- position, topology and attributes.

(1) position errors

In polygon on polygon overlay and edge matching operations, it is likely that there will be pairs of lines which should coincide, but because of differences in digitizing or different sources of the data, they do not coincide. As a result sliver polygons are created along principle polygon edges or at map edges (Figure 3.3).

Sliver polygon removal criteria can be stated as follows:

a) Area criteria:

The area of sliver polygons is normally small. Using pre-defined area tolerances some small sliver polygons can be deleted. This criterion will delete some polygons which are small in area but are not sliver polygons.

b) Area to perimeter ratio

A sliver polygon is long and thin. Area to perimeter ratios can be used to detect and delete these long and thin sliver polygons.

c) Number of arcs

Most sliver polygons have two bounding arcs (Goodchild 1990). If this method is combined with area to perimeter ratios, sliver polygons can be detected and then deleted easily.

After deleting sliver polygons, polygon topology needs to be updated, and the sliver polygons can be replaced by lines along the centre line of the sliver.

Figure 3.3. Sliver polygon problem

(2) Topological errors

Topological errors often occur in the edge matching. Topological errors may be caused by original vector data made at different times or by different persons. The same polygons but on different maps may have different left/right topologies or different polygon numbers. To eliminate these errors, one needs to check input data carefully and makes necessary changes. Algorithms do not exist to determine which map topology is correct.

(3) Attribute errors

The term 'attribute' covers all non positional information about a spatial entity. After polygon overlay, all old attributes are not necessarily valid for the new polygons. New polygon attributes can be calculated from overlay criteria based on the old attributes. As the main effort of this research is to concentrate on vector data itself, attributes data errors are not discussed in detail here.

Automatic digital data error detection and correction are built in some GISs, such as Arc/Info. Arc/Info provide CLEAN and BUILD function to clean errors and build topology. It requires the user to specify gap tolerance or node match tolerance. Due to the nature of difficulty in error detection, many GISs such as MapInfo and ATLAS* does not have similar functions.

An error-free vector data base is essential for geographic data processing. Topological errors are often not visible but must be corrected before any analysis can be performed. Vector data sets normally have large volumes. Large data sets cause inefficient error checking, longer processing and unnecessarily detailed output. The next part of this thesis will concentrate on how to reduce physical points on a geographic entity line.

Chapter IV. VECTOR DATA GENERALIZATION

4.1. Introduction

Generalization is a core concept and process in cartography. Two decades ago, manual generalization dominated cartography, typically in topographical mapping. Compilation from larger scale maps to small scale maps required step wise generalization to gradually smaller scales. The resulting content and appearance of a new map largely depended on the cartographer's experience. To generalize over one river line, or a set of contour lines, or a block of building required many decisions at once by a cartographer. These decisions included selection, curve maintenance, exaggeration, elimination, displacement, combination or separation.

But over the past two decades, the metamorphosis from manual to digital techniques in cartography has resulted in the development of computer algorithms designed to replicate many tasks previously performed by humans (McMaster 1987). The impacts of computers are noticeable in many aspects of cartography. Many sophisticated geographic information processing systems have been developed. The capabilities of these systems for data manipulation and data analysis are very strong especially in thematic map data processing. Choropleth mapping is accurate and fast. But the development of generalization algorithms is slow, compared with other cartographic activities (such as data capture and map production). It is important to explore further digital data generalization concepts and practices.

Since the late 1960s, several line generalization algorithms have been developed (Lang 1969, Douglas and Poiker 1973, Jenks 1981). All these algorithms are concentrated

on one aspect, which is, how to reduce the number of digital points from a line. Many authors ignore the fact that lines may have different meanings and significance on the map. One generalization algorithm which is used for a particular line cannot be used as the basis to generalize all other lines. For example, contour lines cannot be generalized line by line independently. All lines on a map have spatial relationships and other connectivities. A study of objective numerical generalization is conducted in this chapter. The example used is river system generalization. A river is a linear feature, and several rivers comprise a system, which conveys information messages and which may imply some other meanings, such as drainage pattern. Generalization of a river system requires some unique criteria, which are not as simple as those for line generalization. The algorithms used in river system generalization are based on line generalization algorithms and their combination with river system characteristics.

4.2. Generalization concept

4.2.1. Generalization in cartography

Generalization is a map data process to make the map clear and efficient for use for map readers. The mental connection between geographical features and their expression on maps is a complex one (Jenks 1981). Not only must cartographers make this connection to their personal satisfaction, but they must also make others react to the drawing in the intended way. Generalization is one of the most important and complex processes in map

data processing, especially in topographic mapping.

There are two kinds of map data generalization processing. One is from reality to the map -- to select and symbolize features, and then generalize to a map scale. The other is compilation from a large scale map to small scale map which requires selection and simplification of features. Figure 4.1 shows a generalization processing from a larger scale map to a smaller scale map. These generalization processes are discussed in this study.

Figure 4.1. Generalization process example

The two most important generalization steps are selection and simplification. Selection requires selection of important, or large features for small scale maps, or selection of information classes necessary to serve the purpose of the map. Simplification requires delineation of the selected data both to the scale of the map and to the requirements of effective communication.

No modification takes place during the selection process. The choice is either to portray roads or not to portray roads, to select major highways or to include all roads, to

include or not include hydrographic features. In contrast, there is a lot of modification in simplification. If there is no modification in map data processing, there will be no clarity, or some important characteristics of map features will not be identifiable. Reduction is likewise accompanied by unavoidable changes. Distance between features, widths and lengths of features are shortened. Adjacent discrete items become more crowded. The shrinkage of presentation space is what makes it possible to see the geographic arrangement of phenomena, but the increased complexity and crowding tend to compound confusion. Line generalization occurs in simplification.

Figure 4.2. line types

From a technical point of view, a map is composed of points, lines, patterns and colours. They express land, the water system, transportation routes, cities and many other social economic or natural aspects of the earth. One can make a map without colours and points, but cannot avoid using lines. Lines are used to represent rivers, roads, shorelines,

contours, parallels and meridians etc. These lines can be designed in many different styles(in the thickness or in the shape, Figure 4.2).

In traditional cartography, linear features have been of particular interest. River lines, contour lines, political boundary lines require several different unique criteria for their generalization. These criteria are based on the geographic and cartographic characteristics of the feature, map scale and map purpose. Geographic characteristics of features means that these elements have different shapes, sizes, and other attributes in the different geographic zones. These geographic characteristics are portrayed using different cartographic techniques on the map. The most important cartographic technique which is used to represent these geographic characteristics is generalization.

For example, consider two different river systems, one in a high relief area and the other in a plain. The differences between these two river systems which require different selection and simplification techniques to portray smooth lines (plain river) and sharp curve lines (high relief river).

4.2.2. Numerical Generalization

With digital cartographic data used more widely, several new questions arise such as, 'How can we generalize digital data?' or 'How can we use large scale digital data to produce relatively small scale maps?'. Numerical generalization became a new concept and topic in the cartography. From the late 1960s to early 1980s, over ten line generalization algorithms have been developed by several authors such as Lang, Douglas-Poiker, Jenks etc. Recently, these algorithms have been tested and compared by McMaster (1987), Muller (1987) and Brassel (1988). The results showed that any of these line generalization

algorithms are acceptable for a single line generalization, under a variety of conditions and constants.

Numerical generalization is different from traditional map generalization. Numerical generalization depends on computation of geometric characteristics of points, or lines, the results of which determine which points on the line are to be maintained or deleted. Traditional map generalization depends on a cartographer's experiences.

Most previous numerical generalization research has concentrated on geometric line/point reduction, maintaining relative geometric characteristics of the line. Lines were generalized individually without relating one line to another. (Toiler 1966, McMaster 1989).

4.2.3. Objective Numerical Generalization

It is necessary to state that geometric lines on the map have meaning and significance. The characteristics of these lines are different from one to another. From the map reader's view, these lines not only represent geometric lines with width, length etc., but also portray different geographic features such as river and railway networks. One line connects to other lines which have different meanings, and their spatial relationships and connectivities convey specific information. Figure 4.3 shows relationships and meanings for different lines.

It has been recognized that individual contour lines should not be generalized independently, since they represent a continuous surface (Pannekeok 1962, Mark 1989). For a set of contour lines, we cannot simply use line generalization algorithms. Figure 4.4 shows some generalization results which are unacceptable. Contour line 1 and 2 are intersected due to individual line generalization. So for the particular features, we should

develop algorithms that suit their nature. This activity can be called Objective Numerical Generalization. In this research, river system generalization is used as an example for objective numerical generalization.

FIGURE 4.3. Different line meanings

Figure 4.4. Set of Contour lines generalization

Another aspect of Objective Numerical Generalization is scale alteration. Most of the previous line generalization work concentrated on data point reduction at one scale and did not consider scale change. In fact, for an experienced cartographer, generalization must be discussed in the context of some pre-defined scale. Generalization from a large scale map to a medium scale map and generalization from medium scale to small scale maps are different. For example, cartographers try to maintain high locational accuracy on a larger scale map instead of maintaining a geographic pattern as on a small scale map. Thus if we discuss line generalization, we must refer to the scales we are working on.

4.3. Line Generalization

Each spatial entity, portrayed by points lines or areas, is considered within the bounds of a number of coordinate systems that have been developed over a period of many decades. These coordinate systems provide a means of positioning exactly the entities in earth space, and of providing measurements of such attributes as perimeter, area, distance, and direction between entities.

Areas consist of lines. Lines are composed of points. The X,Y coordinates of points are numerical which can be used for geometric calculations. Line generalization is based on geometric calculations (such as distance from a point to a line, distance between two points, and the angle between two vectors). Line generalization is essential for Objective Numerical Generalization. Six line generalization algorithms are reviewed below.

4.3.1. Retaining every Nth point algorithm

This algorithm is the simplest and used very often in line generalization. N is a predefined integer point number, which can be considered for selecting every N th point. The advantage of this algorithm is the short calculation time. Disadvantages are frequent elimination or misrepresentation of important features along the line.

4.3.2. Predefined distance algorithm

This algorithm was originally designed by Tobler (1965). The distance (D) between the present point to the last retained point is calculated and compared with the predefined tolerance (TL). If $D > TL$, then the point is retained, otherwise the point is deleted and D is recalculated to the next point. This algorithm has almost the same advantages and disadvantages as the algorithm to retain every N th point.

4.3.3. Jenks perpendicular distance algorithm

As reported by Jenks (1981), this algorithm calculates the perpendicular distance from a line connecting two points to an intermediate point. The algorithm calculates the distance DT from point C to a line and then compares DT to a tolerance distance TL . If $DT > TL$, point C is selected, otherwise point C is deleted, and then point $C+1$ selected and become another start point for the calculation.

4.3.4. Angular change algorithm

The angle of change between the two vectors is calculated. If this angle is greater than a tolerance angle, such as 5 degrees, the point is retained, otherwise the point is deleted.

This algorithm can be used to detect critical points on a line, such as a river's critical points.

4.3.5. Lang Perpendicular Distance Tolerance Algorithm

Lang (1969) reported this algorithm, as illustrated in figure 4.5. Tolerance TL should be decided first. Point A is a start point referred to as the anchor point. B is a float point. If distance (PT) from point B to line AC is greater than TL , point B is selected and becomes a new anchor point, point C becomes the second float point, and the distance (PT) is calculated from C to line BD compared with TL and the next anchor and float point decided.

Figure 4.5. Lang perpendicular distance algorithm

4.3.6. Douglas-Poiker Algorithm

This algorithm based on the Lang algorithm, was developed by Douglas and was presented in the paper by Douglas + Poiker in 1973. The idea is illustrated in figure 4.6. First point A is selected as the anchor point as Lang, and the last point D is selected to be the first float point. Calculate perpendicular distance from every point to line AD. The maximum perpendicular distance is MaxD. If MaxD greater than predefined tolerance distance TL, then point C became the second float point and C is selected. The same procedure is repeated until $\text{MaxD} < \text{TL}$.

Figure 4.6. Douglas-Poiker algorithm

This algorithm has been considered the most reasonable and correct algorithm. McMaster (1987) concludes that this algorithm can provide better results for line generalization. This line generalization algorithm was coded in some university research programs, but it is not widely built into the current commercial GISs. The Douglas-Poiker

algorithm can be found from some GISs such as SPANS. Many GISs, such as MapInfo and ATLAS*, do not have any line generalization functions. The Arc/Info system only has weed tolerance which uses a pre-defined distance algorithm to do the generalization.

4.4. Line smoothing

In contrast to line generalization routines, smoothing functions geometrically shift points to eliminate shape angularity. Smoothing function add some new points or displace old points in a line and make the line look natural. In a generalization processing, lines are smoothed after line selection and generalization. There are two basic types of smoothing functions.

4.4.1. Basic average weighted algorithm

This smoothing algorithm has been used for over twenty years. Specific types of algorithms include weighted moving averaging, distance-weighted averaging and slide-averaging. The number of points in averaging (three, five, seven...) controls the degree of smoothing on the line.

4.4.2. Spline smoothing routine

Spline is used frequently in CAD and many other drawing packages. Spline uses mathematical approximations to generate new points based on existing points. There are three popular splines in computer graphics, Cubic spline, Bezier spline and B-spline.

The cubic spline has been proved to be one of the most useful tools in computer graphics, mainly because 3 is the lowest degree of a polynomial that allows the existence

of inflexion points.

Cubic spline is not particularly suited for GIS because a change of one vertex implies that the whole spline must be recalculated, resulting in greatly extended computation time. Most CAD drawings are straight line dominated, which does not apply to geographic lines.

French scientist Bezier used a special class of polynomials as the basis, namely the polynomials of Bernstein. Bezier spline requires calculation of the first and the second derivatives at the end point. First derivatives tell us that the slope of a tangent vector at the end point of the guiding polygon is equal to the slope of the first and the last polygon segment. This ensures that the Bezier curve will behave well in the end-point. The second derivative shows that the curvature depends on the two end segments of the guiding polygon.

Each value of the Bezier spline's curve depends on all other values, so that we cannot change the slope of the curve in the middle because that alters the slopes at end points, which are critical points which must be maintained. Due to the complex nature of most digitized curves the Bezier spline does not appear practical for most cartographic applications, although in CAD and engineering drawings where curves are designed rather than naturally occurring, the approach of the Bezier spline is effective.

B-splines form a modification of a cubic spline. The B-spline appears to have more potential for digitized natural geographical curves (McMaster 1989). B-splines can be considered as local lines, a change in the slope of the curve in the middle only results in a change in part of B-splines. Less time is spent in recalculating the curve on the screen, which means faster computer response, and this is very important from the GIS user point

of view. Considering large GIS data setd, fast computing make B-spline more usable in GIS applications. Figure 4.7. shows the result of B-spline smoothing.

Figure 4.7. Spline smoothing (Result from AutoCad)

B-spline appears to be one of the most usable line smoothing algorithms in GIS applications. Future GIS applications could use B-spline as a basic smoothing function.

In this chapter the author has introduced objective numerical generalization concept. Many of these objective numerical generalization concepts, data encoding, data errors and line generalization problem and practice are discussed in the following chapter in river system generalization scheme.

Chapter V. River system generalization

In the chapter IV, an objective numerical generalization concept was introduced. A river system is selected as an example of objective numerical generalization in this chapter.

A river is one of the most distinctive natural elements on the surface of the earth. Running water is the most effective agent by which the surface of the earth is sculptured.

Because of the importance of water to human life, as well as to transport and aesthetics, a river is always represented on topographic and many political and economic maps.

A river is represented by a line or lines on maps. These lines represent the river length, river location, river width and pattern of the course through a region. In order to generalize rivers, rivers should be encoded, selected, and generalized according to objective numerical generalization rules.

5.1. River drainage pattern and network ordering

5.1.1. Drainage patterns

The drainage basin and the drainage patterns are intimately related, for the basin represents the gathering ground of water which flows in the river. Although the drainage system does not express directly regional characteristics such as geology and topography, it implies some characteristics of geological form such as folded sedimentary rocks or rectangular drainage for jointed crystalline rocks.

Eight drainage patterns - dendric, pinnate, parallel, trellis, rectangular, angular, radial and annular are well recognized in geography. These drainage patterns should be portrayed very well on a map, so that map readers can imply basin characteristics. For a map maker,

one of the most important tasks is to express a feature's characteristics clearly on the map, either directly or indirectly. On large scale maps (1:50,000 and larger), almost every river and stream can be portrayed. But on small scale maps (for example, 1:250,000 and smaller) only a few of the real world rivers can be portrayed. A large number of rivers will be deleted because of the map scale, for the sake of map clarity. These limited rivers will be used not only to portray the position of a river, but also to portray the regional geographical and geological characteristics. Sometimes this task is more important to achieve than river locational accuracy on the map. In order to express regional geographical characteristics, several methods are used in map generalization.

5.1.2. Drainage pattern recognition.

Human identification of drainage patterns can be accomplished through map reading or aerial photo interpretation. Computer assisted pattern recognition has been applied in river drainage pattern recognition. Argialas (1986) described a drainage pattern analysis system. Comprehensive qualitative descriptions of drainage patterns were completed by Zernitz (1932), Pavis (1950) and Howard (1967). These qualitative pattern definitions show that their descriptions are based on the identification of specific objects (main stream, primary and secondary tributaries). These specific objects can be characterized by certain attributes (e.g., elongation, straightness, uniformity), and relationships among them (e.g., perpendicularity, parallelism). Selection and extraction of pattern attributes, to generate pattern models and to design a strategy for classification, are required in pattern recognition (Thomanson 1981). In order to recognize drainage patterns, according to their definitions,

one needs to extract three types of main objects: the main stream (trunk), the primary tributaries (branches) and secondary tributaries (leaves). These three objects will correspond to the third, second and first Horton orders (Horton 1945). Main stream shape, branch shape, mean intermediate angle of streams and other pattern attributes are required.

Based on pattern attributes, Argialas (1986) proposed a system that fills in the attribute values according to the definition of drainage patterns. Each pattern is assigned to one of the eight predetermined classes.

Although this is a good theoretical frame work for drainage pattern recognition, computational approaches to drainage pattern recognition are still limited.

5.1.3. Ordering of river network

In order to carry out pattern recognition and river network generalization, rivers are classified or ordered first.

The earliest attempts at a formal ordering scheme were undertaken by Gravelius(1905) (in Woldenberg 1968). He ordered the river to reflect the age of the river. The oldest river of the network, assumed to be the trunk, was designated order one. The primary tributaries were designated order two, and the fingertip streams were designated the highest order. Horton (1945) inverted the numbering, making the main trunk the highest order, and fingertip rivers first order. The Horton ordering scheme makes all the fingertip tributaries except the trunk stream to be of the same order. So a relation between the order and the number of links could be determined. Horton's scheme is of interest to map makers because it uses systematic rules to identify the main trunk.

To determine the parent between a tributary stream and an up stream segment from the bifurcation being considered, the following rules may be used: (1) starting below the junction, extend the parent stream upstream from the bifurcation in the same direction. The stream joining the parent stream at greatest angle is of the lower order. (2) If both streams are at about the same angle to the parent stream at the junction, the shorter is usually taken as of the lower order (Horton 1945).

Figure 5.1. Horton ordering scheme

Later Strahler(1964) and Shreve (1966) modified Horton's ordering scheme. But the basic scheme reflecting importance of a river Horton's.

5.2. River network encoding, critical detection and river selection

5.2.1. River network data encoding

River entities can be defined as all linear features built up of straight line segments made up of two or more coordinate pairs. One simple river can be portrayed by several coordinate

pairs plus a possible record indicating the display symbols to be used. For example, the display symbol parameter could be used to call up solid lines (Normal rivers) or dashed lines (Seasonal rivers).

Each river network has a unique arrangement of a main trunk and several branches. These rivers constitute a topological tree. A river network is also an arrangement of links and nodes interrelated with each other in such a way that new links merge into existing links.

Probably the simplest method of river line storage is as an arbitrarily long string of scale-specific coordinates, representing either a named river or part of that named river. For variable scale access, the named river could be stored at a single high resolution and generalized at the time of retrieval, or multiple scale specific versions can be stored. To organize an efficient river network in digital form, the following coding methods were developed for use in this research.

1 River by River Coding

The Figure 5.2 illustrated that the main stream was coded No.5. Other tributary rivers were coded in sequence. The main advantage of this coding is its simplicity. Digitized river by river, the nodes (one of kind of critical points) carry the connectivity information of the drainage pattern. The generalization algorithms are based from river to river manipulation. Figure 5.3 illustrates the topological relationships between entities.

Figure 5.2. River by river coding

River	Flows to	To node
1	2	D
3	2	C
2	5	E
4	5	A
6	5	B
7	8	H
9	8	I
8	5	F
10	5	G

Node	In	To (River)
A	4	5
B	6	5
C	3	2
D	1	2
E	2	5
F	8	5
G	10	5
H	7	8
I	9	8

Figure 5.3. River by River Topology

2 Segments and nodes coding

In this data structure (Figure 5.4), we can see the "main" river was coded by sequence 2,3,5,11,17,19. The nodes divide the main stream into several segments. This indicates that generalization algorithms will be based on the segment to segment manipulation. The nodes A...I carry the connectivity information of the drainage. Figure 5.5 illustrates this method's topological relationship between the entities.

Figure 5.4. Segments and nodes coding

Segment	Flows To	To Node
1	3	A
2	3	A
3	5	B
4	5	B
6	8	C
7	8	C
9	10	D
8	10	D
5	11	E
10	11	E
12	14	H
13	14	H
15	16	I
14	16	I
11	17	F
16	17	F
17	19	G
18	19	G

Node	In	To(River)
A	1,2	3
B	3,4	5
C	6,7	8
D	8,9	10
E	5,10	11
F	11,16	17
G	17,18	19
H	12,13	14
I	14,15	6

Figure 5.5. Segment and nodes topology

3 A river tree

In contrast with conventional vector data recording, a multi-scale river tree structure was developed based on multi-scale line tree structures. Jones (1987) proposed a line tree structure (Figure 5.6). It is generated by using a line generalization algorithm to classify the internal points into a separated number of levels of scale-related significance (there in Figure 5.7). The highest level of tree (A,B,C,D) contains the most significant, smallest scale representation, while lower levels provide progressively greater intermediate detail. The tree is traversed to whichever level is adequate for the scale requirement, and thus only those points required are accessed, while data duplication between levels is avoided (Jones 1987). The coding method associates with each point a left and right control value which records the number of adjacent intermediate points at the next level down the tree (Figure 5.6). Each level of a tree is stored in logically independent records or files.

A river tree not only has different level points in one river, but also has different river levels in a river network (Figure 5.7). Top level in a river network is a main river, followed by levels which are branch rivers. River levels could be determined by the river network or drainage pattern (the network determined in Figure 5.7). The implementation method associates with each point a river level code, a left and right control value. Points are stored in logically independent records or files based on points level of the tree.

FIGURE 1. a Points selected at three levels of generalisation using the Douglas-Peucker algorithm. Circles mark the most significant points, and squares and triangles mark additional points selected at successively reduced tolerances. When subsequently retrieved, only the points relevant to the given scale will be accessed. b Line tree constructed from these points, with left and right control values. Note that the tree can also be stored by replacing the control values with point sequence numbers which uniquely identify points so that they can be sorted in the correct order at the time of retrieval.

Figure 5.6. Multi-scale Line tree (after Jones 1987)

A	B	C	D	E	i'	G	H	I
a b	c		h	e g		l	c d	m
A,B,C,F,G				first level points on main stream				
D,E,H,I				second level points on branch				
a,b,c,d,e..				third level points on branch				
1,2				fourth level points on segment				

Figure 5.7. A river tree

5.2.2. RIVER SYSTEM CRITICAL POINTS DETECTED

1 Critical Points

In objective numerical generalization processing, some important points should be kept in place before any points are reduced and shifted. These points are called critical points or characteristic points, and they have been discussed widely by different authors in previous years. Marino (1979) defined critical points as "Those points which remain more or less fixed in position, resembling a preciseness of the written essay, capture the nature or character of the line". For the cartographer who wishes to retain the basic character of the line, critical points are selected prior to the other generalization steps. In computer cartography, this issue is more important than others. Simple line generalization algorithms as discussed earlier may maintain some critical points, but may lose some critical points as well.

Freeman (1978) stated that critical points include maxima, minima, points of inflection, discontinuities in curvature, end points, intersections, and points of tangency.

White (1985) conducted an experiment to assess line generalization algorithms using critical points. He created a baseline of perceptually chosen critical points to be used in the experiment to evaluate line generalization algorithms. Three line generalization algorithms were used. There were Nth point elimination, the perpendicular distance, and Douglas-Poiker algorithms. Three criteria were compared between computer-generalized lines and a perceptual base line: areal offset, number of points common to a perceptual base line and its respective computer generalization; and perceptually weighted critical-point comparison between computer generalization and its corresponding base line. The measure remaining

was a visual comparison by respondents of generalized lines and the original lines they were meant to represent. In all cases the Douglas-Poiker algorithm produced the best generalization results. Although the Douglas-Poiker algorithm can provide relatively accurate generalization, still some critical points may be lost in the generalization (Li, 1988). For objective numerical generalization, there are different ways to detect critical points for different features. The following examples are based on river system generalization.

2 River System Critical Point Detection

For objective numerical generalization, critical point detection should be conducted before line generalization. In river system generalization, the intersection point of rivers is more important than other critical points. Figure 5.8 shows the generalization result when a branch is not connected with the main stream, i.e., the critical points were not detected.

Figure 5.8. No critical points detected error

In the previous section, there are three data structures which were proposed in the river system. For each data structure, the critical points detection method is different.

For river by river data structure, the following critical point detection methods will be used:

The First Method:

- (1). Find the end point $P(X,Y)$ of each branch river
- (2). Create a table that includes these points
- (3). Select $P(X,Y)$ coordinates in the main stream. The $P(X,Y)$ coordinates become the critical points in the main stream.
- (4). Retain these points in the table and use a line generalization algorithm to generalize river lines between these critical points.

The Second Method:

- (1). Make sure digitized intersection points (or nodes) are correct in the digitization process.
- (2). Create a nodes coordinates table as a critical point table.
- (3). Make the branch end points $P(X,Y)$ equal the nodes coordinates
- (4). Use a line generalization algorithm between the critical points while retaining these critical points.

For Segment Data Structure, it is easy to maintain these critical points:

- (1). The beginning and end point of every segment are the critical points.
- (2). Create a table which contains beginning and end point coordinates.
- (3). Generalize from segment to segment while retaining these critical points.
- (4). Generalize branch streams.

For a river tree structure (Figure 5.7), critical points are those high level points. These different level points need to be maintained during the process according to generalization rules.

5.2.3. River selection

River concept used in the following calculation is illustrated in Figure 5.2 (p 61). There are 10 rivers in Figure 5.2. River 5 is the longest river.

The following river elements were used in this research.

- 1). River length (calculated from beginning point to end point of a river) and width (average width of a river).
- 2). Distance between rivers dimension (average distance between two rivers, normally between parallel rivers).
- 3). Maintain the relative river density ($\text{RIVER DENSITY} = \frac{\text{The total number of rivers}}{\text{Area of drainage}}$ or $\text{RIVER DENSITY} = \frac{\text{The total number of rivers in one Drainage}}{\text{The area of drainage}}$).
- 4). Importance of a river (higher river ordering, and drainage pattern recognition).

5.3. A River Generalization System

5.3.1. A proposed generalization scheme

The process for generalizing a river system is as follows.

- 1). Assign river levels by using Horton's ordering.
- 2). Use river by river coding method to record data.
- 3). In theory, there must be a maximum river density on a map. We assume this maximum density is MD. MD varies from scale to scale, region to region. But there is one MD for one specific scale and region. This MD can be calculated from existing maps.

4). Drainage pattern recognition

Drainage pattern recognition can assist in determining a river's importance in the selection rule. For some river systems it is vital that the drainage pattern should be maintained.

- 5). In reducing a map from one scale to another relatively small scale map, the river network will be crowded and the river density on the reduced map may become high. We assume this density is AD (Actual Density). AD can be calculated by the computer easily.

6). If AD (Actual Density) bigger than MD (Maximum Density), that mean scale map needs to be generalized, otherwise, the scale map does not need to be generalized.

- 7). We assume TOL is a tolerance. If $AD - MD = ED$ bigger than TOL, that means ED is extra-information on the new map, and the map needs to be generalized.

8). Establishing selection rules

There are several river characteristics which can be used to determine which river will be selected or which river will be deleted. The following formula is used to define river weight.

River weight = (length / maximum length) + (width / maximum width) + (distance / maximum distance) + (importance/ maximum importance)

9). Delete the lowest weight river (No.8) (Table 5.1.) and then calculate AD-MD=ED again, if ED<TOL, stop generalization. If ED > TOL then delete next lowest weighted river (No.6), and so on, until ED<TOL.

10). Save the remaining data into data base.

Table 5.1., River Weighting

River No.	Length (MM)	Width (MM)	Distance (MM)	Importance	Others	Final Weight
1	180	3	30	10		4
2	170	2	10	9		2.8
3	160	1.5	15	8		2.9
4	100	1	19	7		1.9
5	30	0.7	15	5		1.4
6	6	0.2	11	2		0.7
7	60	1.1	6	6		1.5
8	3	0.15	5	1		0.23
9	19	0.9	11	5		0.97
10	11	0.7	13	5		0.92

5.3.2. The diagram of the River Generalization System

Figure 5.9. River generalization system

CHAPTER VI. CONCLUSION

Through this research, several critical elements to make system more accurate and useful have been studied. A multiple coordinate system is suggested to record topological data more accurately. Topological encoding and errors correction methods are studied to eliminate data errors. Objective numerical generalization schemes are proposed to make result more precise and useful.

For recording X,Y coordinates, future GIS software should use more than one coordinate system. Multiple coordinate systems are being recommended because they can run on a variety of devices and have convenient measurement units. A matrix transformation scheme between different coordinate systems is required.

Vector data structures have been widely used in GIS for a long time. Topological relationships between spatial data must be expressed explicitly in vector data structures. Topological data encoding on points, lines and polygons must be carefully studied. Four topological encoding methods have been found through this research. They are whole polygon topology, arcs with centroid topology, arcs with area list topology and arcs with left/right topology. Whole polygon topology is inefficient, time consuming, and has poor output data structures. It should be avoided in future implementations in GIS software. Arc with area list topology and arcs with left/right topology are recommended for future implementation. They are efficient, more logical, easy to edit and have high quality output advantages.

Island topology has been paid more attention. Island topology is the most difficult part in topological vector data creation and manipulation. How to express island topology

more efficiently and clearly still needs some research, but to date the most efficient method appears to be arcs with left/right topology and area list topology.

Vector data errors can be detected and deleted by computer program. This study has explored the causes and correction of vector data errors. Topological data inconsistency are the main problem in vector data. Topological data inconsistency can be detected and corrected automatically. Automatic searching and correction on all vector errors need further research.

Line generalizations have been developed very well in terms of algorithms. Objective numerical generalization is based on the concept that geometric lines on maps also have meaning. Lines which represent different objects should have different generalization criteria. A river generalization system has been created. Criteria for a river generalization system include: river length, river width, the distance between rivers and regional geographic characteristics. Algorithms and criteria for other objective numerical generalization need to be explored.

Most of this study are based on theory frame work. Further testing and computer coding are necessary. The author would like to implement some of these theory in the future research.

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