MODULARIZATION OF DIGITAL CARTOGRAPHIC DATA CAPTURE

Robin G. Fegeas
U.S. Geological Survey
521 National Center
Reston, Virginia 22092

ABSTRACT

The capture of digital cartographic data, including digitizing, is currently one of the most expensive and labor intensive operations in the field of automated cartography. As a step toward reducing these data capture costs, structured analysis techniques are applied. Map features may be typed by dimensional extent: points, lines, areas, and volumes. Digital cartographic data describing these features may consist of three distinct subsets of data: (1) locational or image; (2) non-locational or attribute; and (3) topological (neighborhood or adjacency). Methods of isolating the capture of each of these data subsets into discrete functional modules and sub-modules are explored. As newer methods of performing these separate functions are developed, they may be "plugged in" as modules without developing new data capture systems.

INTRODUCTION

In recent years we have seen many advancements in the use of digital computers for handling cartographic data. Better ways are being developed for representing, storing, retrieving, manipulating, analyzing, and displaying cartographic data. With the increasing performance and decreasing costs of computing hardware, the dream of using these machines to better help us understand and manage our land and its resources is becoming a reality.

But the initial data capture step remains the primary limitation to the production and use of digital cartographic data. The costs of transferring data on existing graphic maps into machine-readable, and machine-useable (readable is not necessarily useable) forms continues to be high. This is especially true when they are compared to the much lower costs, relatively, of almost all other phases of automated cartography and spatial data handling. Even such complex tasks as polygon overlay, areal generalization, and map compilation (including automated name placement) are, or soon will be, realistically cost-effective processes for large-scale and small-scale endeavors (such as those engaged in planning, marketing, spatial process modeling, or mapmaking). Now, with the exception of simple, low-volume data, this is not the case for digital cartographic data capture.

As with most data input procedures, the high cost of capturing digital cartographic data is related to the level of manual labor required. Manual operations involve preparing source materials for digitizing, coding, verifying, validating, and editing, as well as actually digitizing. The amount of labor required is usually related to the quantity and types of data, both input and output, to be processed. But other labor costs are also incurred as "overhead" of the particular system and set of procedures used in the data capturing process. Some overhead costs are, of course, unavoidable. Poor system design, however, or the inappropriate usage of equipment, systems, and(or) procedures (which may be cost effective for one level or type of data but not for another) also increase costs. If systems could be tailored to the differing requirements of various data levels and types, progress could be made toward reducing data capture costs.

STRUCTURED ANALYSIS METHODOLOGY

The techniques of structured analysis may afford a means of specifying systems for capturing digital cartographic data. These techniques concentrate on the modularization (partitioning) of a system based upon the flow of data, definition of data components, and minimization of interfaces among data transformation processes (DeMarco, 1979). An activity to be modeled consists of two types of entities: data and processes. Data may be considered as the passive entities (or objects) of an activity. Processes are the active entities (or verbs) of an activity and are defined initially by their data inputs and outputs. An activity is ultimately modeled by the diagramming of data flows which ties all data and processes into one coherent systematic description.

Structured analysis further facilitates modularization by the top-down hierarchical approach to the definition of processes and data. An entire activity may be considered as one process with data inputs and outputs. It is then further partitioned into sub-processes, each with its own data inputs and outputs, until the lowest level of functional modules have been defined. The method of partitioning is not from a functional (or internal process) viewpoint, however, but from the view of the data. An analysis follows the data through an operation, concentrating on distinctions among data inputs and outputs. Functional modules are the result of the methodology, but data and data flows are its driving force.

One principal feature of system designs based upon this methodology is a high degree of module independence. The less the internal implementation of one module (how its function is performed) depends upon another module, the more independence is achieved. This greatly facilitates maintenance and adaptation of a system to changing requirements and improved techniques.

DIGITAL CARTOGRAPHIC DATA COMPONENTS--PART I

The first step in modeling the data capture process is to define its data inputs and outputs. This also presents the opportunity to outline the context and scope of the present definition of the data capture process. The input to the data capture process is defined here as a cartographic representation (i.e. a graphic map) of phenomena on some portion of the Earth's surface (or any portion of space), possibly including non-cartographic data which describe the same phenomena. The output is a digital representation of the same data about those phenomena or some subset of that data. Since the data input to and output from the data capture process may be considered the same, only in different forms, cartographic data may be discussed in the abstract, regardless of form.

The real component of a cartographic data set is called a "feature." A feature, to review this basic cartographic term, is some object or cohesive phenomenon on or near the Earth's surface which may have some significance. Examples of features include a building, road, stream, woodland area, spot elevation, town, county boundary, etc. All other components described below are actually characteristics of either individual features, or of a collection of features most term a "map" or an "overlay."

Feature Types Based Upon Dimensional Extent

One method of partitioning cartographic data is by dimensional extent. Feature dimensional extent may be of one of the four dimensions: zero for point features, one for linear features, two for areal features, and three for volumetric features or surfaces. Actual features may contain entities of more than one dimensional extent, but for now assume features are entities of a single dimensional extent type. Hereafter, when reference is made to a feature type, it is based solely upon its dimensional extent.

Dimensional extent may refer to both real world and digital representations. It should be noted that many real world volumetric and areal features will have digital representations as points or lines, depending upon the spatial resolution of the digital representation. Most often rivers and transportation routes will be represented as linear features even though they occupy areas on the Earth's surface. When this is taken into consideration, it can be seen that there may actually be four feature types in the real world, but theoretically up to ten types when coupled with their possible digital representations (see table 1).

	Digital Representation			
Real World Extent	point	line	area	volume
point	0-0			
line	1-0	1-1		
area	2-0	2-1	2-2	
volume	3-0	3-1	3-2	3-3

Table 1. Digital cartographic feature types

DIGITAL CARTOGRAPHIC DATA COMPONENTS--PART II

The next partitioning of digital cartographic data is based upon the logical types of data which may be used to describe either a given feature or collection of features. These components are classified under three broad categories of descriptive data types: (1) locational data, (2) attribute data, and (3) topological data.

Locational Data

Locational data fix a feature or set of features in space, usually using some reference system relative to known locations upon the Earth's surface. Spatial extent, geographical extent, and absolute position are all terms synonymous with location. Space, of course, is three-dimensional so the normal means of specifying a location in space is with the use of X, Y, and Z coordinates relative to three mutually perpendicular axes. For most cartographic data, however, the third or Z coordinate is unexpressed (or suppressed). The data are assumed to exist upon the Earth's surface which is in turn assumed to be a plane or a spheroid.

Note that the logical form of the locational data required to fix a given feature type in space is usually a direct function of the feature type. Within a given cartographic data set, the locational data of all features of one type (e.g. areas) are usually defined in the same logical manner. Conversely, the logical forms of the locational data of different feature types are usually different.

Sub-components of cartographic locational data include resolution, coordinate system specifications, and positional accuracy. Geometric (measurement) data may be derived from locational data.

Attribute Data

Attributes are the non-locational and non-topological data attached to a feature, to a collection of features, or to an entire data set. These data may consist of textual descriptors, discrete feature codes, continuous "Z" values, and(or) some unique label identifier. Ideally, this component should not contain data derived from or indicative of any other feature component (location or topology). Important sub-components of attribute data include theme and category/feature classification system.

Theme concerns the overall classification of the content of a cartographic data set. Ideally, a given data set would consist of only one theme which should constitute a coherent description. Such descriptions of the Earth's surface fall into three broad categories:

- o Artificial subdivisions and features such as administrative, political, census, and ownership boundaries as well as reference systems such as public land surveys;
- o Physical phenomena on (or near) the surface. For example, the overall theme of land use and land cover includes all relatively static (stable) physical phenomena on the Earth's surface; and
- o Surface definition such as hypsography.

A classification scheme (category/feature codes) should be a comprehensive and systematic method of coding all the features of a data set in the context of theme. Note that the classification/feature coding scheme should be structured as much as possible on the basis of the real-world features themselves, rather than their cartographic or digital representations.

Topological Data

Topology refers to essentially nonmetric spatial relationships among the various features on a surface. Topological relationships are not changed by geometric distortions or transformations of the surface as long as the surface is not disrupted. The definitions of the terms "neighborhood function" (Peucker and Chrisman, 1975) and "adjacency" are derived from topological relationships. They reflect an overriding need in the analytical use of cartographic data to know the position of a feature, not only in absolute space, but also with respect to its neighboring features.

The discussion of topological data has been restricted to cartographic data describing features on a continuous surface (e.g. a portion of the Earth's surface), excluding the definition of the surface itself. Feature types are then restricted to three digital representations: points, lines, and areas. To be able to derive the full benefit of topological data, however, it is necessary to further define the entities which may exist within the data set.

All linear features of the data are defined as a set of one or more arcs. An arc is a one dimensional entity whose location may be defined by an ordered series of two or more points, beginning at a node and ending at a node, but not passing through a node. A node is a zero dimensional entity defined as the beginning or ending point of an arc. The only points on the surface shared by any two arcs are nodes (two adjoining arcs share a node). Areal features are defined as a set of one or more polygons. A polygon is a continuous two dimensional entity bounded by one or more sets of adjoining arcs. Each arc set begins and ends at the same node. If more than one set is required to define the polygon, one of the sets is the "outside" boundary of the polygon and the others are separate "islands" within the outside boundary. The cartographic surface consists of polygons which are mutually exclusive and which completely exhaust the surface. Arcs must either define a boundary or portion of a boundary between two and only two polygons (adjacent polygons share an arc), or be totally contained within one polygon. In this set of definitions, point features may be represented as "degenerate" arcs (with only one point unconnected to any other arc), or as true node points shared with one or more arcs.

For data defined in this arc-node-polygon structure, the following topological relationships exist (see table 2): (1) for each arc, (a) arc(s) adjoining, (b) start-node and end-node, and (c) polygon-right and polygon-left; (2) for nodes, (a) arc(s) terminal, (b) nodes sharing arcs, and (c) polygon(s) adjacent; and (3) for polygons, (a) bounding arc(s), (b) bounding node(s), and (c) polygons adjacent. Other relationships may be derived from these (e.g. second and third order neighborhood functions), but these relationships may be considered the primary ones.

		Arcs	Nodes	Polygons
(1)	Arcs	(a)	(b)	(c)
(2)	Nodes	(a)	(b)	(c)
(3)	Polygons	(a)	(b)	(c)

Table 2. Arc-node-polygon topological relationships

Note that there are several redundancies in these relationships. All relationships may be derived from just the start-node and end-node and polygon-left and polygon-right of arcs, and even these relationships are symmetrical (Corbett, 1975). To reverse the order of the points of an arc is to reverse both the start-node and end-node, and the polygon-left and polygon-right relationships.

A PROPOSED CARTOGRAPHIC DATA CAPTURE MODEL

Once a cartographic data set has been broken down into components, a simple model of the data capture process can be built. The model must, of course, include inputs as well as outputs. It is assumed, however, that the inputs and outputs of the data capture process may be considered, with some exceptions, to be logically the same, only in different forms. We begin with points, lines, and areas displayed on a graphic map and we end with points, lines, and areas in digital form.

The model cartographic data set has been partitioned by both feature type and by descriptive data type. The matrix of these two methods yields a framework by which the data capture process may be modularized (see table 3).

	<u>Descriptive Data Type</u>		
<u>Feature Type</u>	Location	Attributes	Topology
Point (0)	0a	0b	0c
Line (1)	1a	1b	1c
Area (2)	2a	2b	2c
Volume (3)	3a	3b	3c

Table 3. Feature type by descriptive data type components

In the ideal digital cartographic data capture model, each of the 12 components in table 3 would have one or more separate data capture process modules. The inner workings of each of the modules would be independent of the internals of other modules. Simply stated, the collection of location, attribute, and toplogical data should be separate operations; and capture of point, line, area, and surface data should likewise involve separate procedures.

Other methods of partitioning the cartographic data set, particularly those more oriented to the input data, will provide definitions of further data capture modules. The consideration of real-world dimensional extent versus digital representation (see table 1) might dictate distinct submodules for a given feature type. In addition, subpartitioning of attribute data, especially by overall theme (i.e. category), will generate other data capture submodules.

Standardizing Data Input

In order to develop a pratical data flow diagram of the data capture process, attention must now be directed to the input side. If input consists of two dimensional objects--graphic maps or images (aerial photographs or other remotely sensed images), an initial distinction can be made between (1) volumetric or surface definition data and (2) planimetric data of point, line, and areal features.

Volumetric/surface data require either (a) a pair of input two dimensional images, or (b) a reduction to one two-dimensional object (e.g. contour lines) plus associated "Z" values which may be considered attribute data. The second case may be considered, for data capture purposes, a type of planimetric data. The first case, however, requires a separate data capture process. The first case will not be considered further here, except to say that some process may be defined which results in the second case.

The first step in the data capture process, therefore, is the standardization of the input data to point, line, and areal features on a two-dimensional graphic map. This is often a generalization step which, in most cases, is part of the normal (i.e. manual) map compilation process. The output from this step consists of two parts: (1) a line graph, the graphic representation of points, lines, and areas, and (2) attribute (including "Z" values) data associated with either collections of features or individual features. These attribute data may or may not be physically part of the graphic map and may be textual and(or) graphically symbolized.

A Proposed Data Capture Flow

The digital components of the matrix in table 3 (minus the volumetric feature type) may now be related to the "analog" input data by diagramming the processes and data flows between them (see figure 1).

Attribute Encoding. The collection of non-graphic attribute data has been covered elsewhere (e.g. Wooldridge, 1974). The present discussion of non-graphic data capture will be limited to the processes by which the non-graphic attributes are related to locational and(or) topological data. Some attribute data, however, may exist in graphic form (e.g. symbolized transportation routes and color-coded areas), and may involve quite different encoding processes. But from the viewpoint of the flow of data (inputs and outputs), all attribute encoding processes are fundamentally similar and, more importantly, logically separate in concept from the capture of location and topological data.

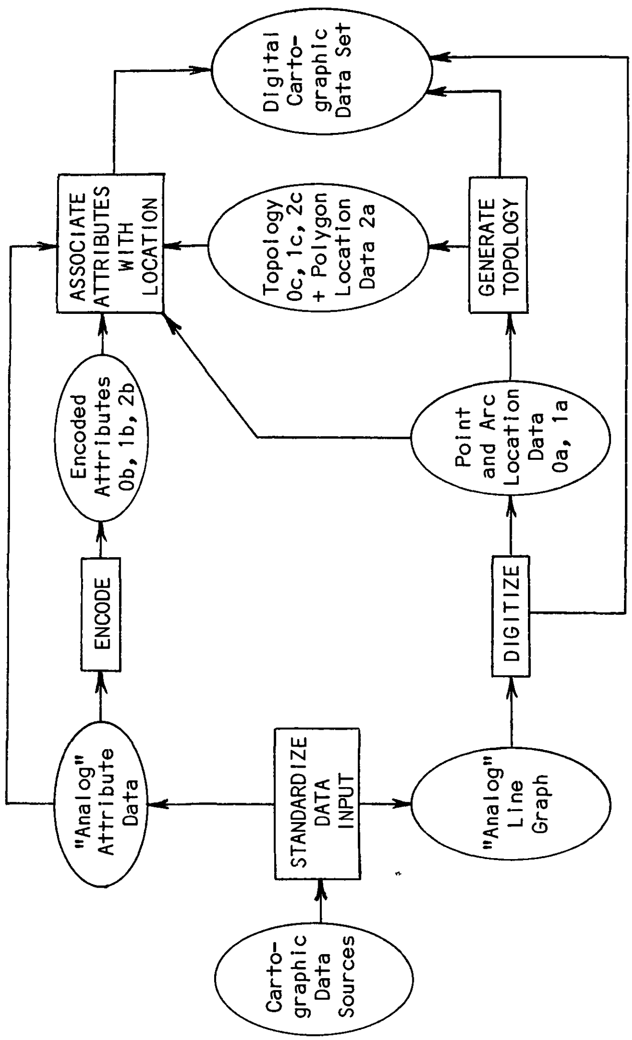

Figure 1. Digital cartographic data capture flow diagram

<u>Digitizing location data</u>. The line graph, independent of attributes, may be seen to consist of the entities (arcs, nodes, and polygons) outlined under the discussion of topological data above. Since polygons may be defined by their sets of arcs, and nodes are defined as end-points of arcs, the capture of all locational data can be considered as the digitizing of arcs. Point features are special cases (either nodes or one-point arcs) and may be handled differently. Digitizing the line graph therefore consists of two processes, each yielding a set of location data--one for point data and one for arc data.

<u>Generating topology</u>. Once the point and arc locational data have been digitized in a logically correct form (different methods of performing these processes may require

various editing and clean-up sub-processes), all first-order (primary arc-node-polygon relationships) topological data may be derived automatically. This is possible because of the initial standardization of the graphic input map into line graph form. The topological relationships among the entities of the graph, although independent of _absolute_ fixed location, are inherent in the _relative_ positions of the entities. Location, therefore, dictates topology. Also, the locational data of polygons (defined by the arcs which bound them) are inherent in the topological data.

Associating attribute data. At this point, all that remains necessary to complete the descriptions of the individual features are the processes which tie the attribute data to the locational and topological data. These processes have traditionally been part of the initial digitizing or encoding processes. As the position of a given feature is digitized, attribute data are encoded at the same time. It is proposed here to isolate, as much as possible, the collection of all three descriptive data types. This does not mean that the association of attribute data with locational data should not be allowed at initial digitization. Although separate processes are recommended, the association process should be possible at any time, for any features.

Note that in figure 1 a number of separate processes have been combined for the sake of simplicity. The association of attribute data with the locational and topological data might involve separate processes for each feature type. The digitizing of point and line data might also involve separate processes, with the understanding that some editing and verification procedures would follow the initial digitization. The generation of all topological data, however, is seen as one basic process with possible point and line subprocesses.

All processes diagrammed at the level shown in figure 1 can be broken down into sub-processes and further. This is a first attempt at an overall first-level partitioning of the data capture process. Before any practical design can be based upon the diagram, much more work must be done.

IMPLEMENTATION CONSIDERATIONS

The actual manner in which the various data capture subprocesses are implemented, as has been noted, should be a function of the characteristics of the specific cartographic data to be captured. Most characteristics having impact upon the data capture process have been categorized and generalized above by feature type and descriptive data type.

Data Volumes. One important data characteristic not covered above, and which does have impact upon the data capture process, is the volume of data. The manner in which data are most efficiently collected from a graphic map with a few sparse features (e.g. a county map of Delaware) might be quite different from the best methods to collect densely populated, high-volume data (e.g. a 20,000 polygon land use map of Connecticut).

Data Structures: An additional consideration which may seem to be important is the logical data structure into which the captured data will be placed. The entire discussion so far could be construed to relate only to the arc-node-polygon topological data structure. There are other structures used to handle cartographic data--"pure images," raster data, grid cells, "pure polygon," and "spaghetti" (Chrisman, 1974). It is proposed here that for point, line, and areal features, all cartographic data structures in use today may be derived automatically and efficiently from the arc-node-polygon structure. Furthermore, the logical view of the input graphic map as an arc-node-polygon line graph does not necessarily mean that the generation of the topological data is mandated, or even that a vector (as opposed to raster) organization is required. The logical components of a digital cartographic data set, regardless of structure, are outlined in table 3. The differences among structures relate to the internal organization of these components, and to the absence or presence of certain components.

CONCLUSION

An initial attempt has been made to apply structured analysis techniques to the definition of the digital cartographic data capture process. These techniques partition a process into functional modules by defining data inputs, outputs, and flows. The resulting discrete data capture modules, defined from the viewpoint of the data, should exhibit a high degree of modular independence. The inner workings of one module should be isolated as much as possible from those of other modules. Such isolation will allow the most flexible use of different methods of capturing the different cartographic data components. The specific methods used may be tailored to the characteristics of a given cartographic data set. Also, as newer and more efficient methods are developed to perform the various data capture sub-processes, they may be "plugged in" without developing entire new systems.

REFERENCES

Chrisman, N. 1974, Cartographic Data Structures Panal: Proceedings of the International Conference on Automation Auto-Carto I, pp. 165-176

Corbett, J.P. 1975, Topological Principles in Cartography: Proceedings of the International Symposium on Computer-Assisted Cartography, Auto-Carto II, pp. 61-65

DeMarco, T. 1979, Structured Analysis and System Specification, Prentice Hall, Englewood Cliffs, New Jersey

Peucker, T.K. and Chrisman, N. 1975, Cartographic Data Structures: The American Cartographer, Vol. 2, No. 1, pp. 55-69

Wooldridge, S. 1974, Computer Input Design, Petrocelli Books, New York