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Data and knowledge modelling for generalization

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Foreword — Generalization: precision variation or change of perception level?

There is a classical tendency to think that generalization consists of selecting a source of information with a given precision factor and in simplifying its geometry in order to represent it with less precision. Thus, generalization should be essentially a geometric computation process consisting in analysing and simplifying geometric characteristics of features as well as their spatial relations. Information needed to generalize is supposed to be contained in initial data and completed by a visual recognition of geometric characteristics and spatial relations. This assumption may hold in the case of manual or interactive digital generalization. The underlying hypothesis is that there is a sufficient amount of information in the initial database to carry out only one possible data generalization. As a matter of fact, when a map or a database is being produced, only one type of information is chosen. Obviously there is no such thing as being exhaustive, even in a topographic map which is basically supposed to represent distinguishable geographic features. A topographic map is a clever compromise between a map of relief, land use, names, settlements, hydrography and communication networks (Cheylan, 1989). A map is a view of the world, and basic maps produced by National Mapping Agencies (NMAs) show this compromise corresponding to a common need. A map corresponds to a particular view of a geographic space (Piron, 1993). The perception of geographic space changes with the change in scale. When the scale varies, space can no longer be depicted in the same way, by using the same objects. Conversely, a change in perception induces a change in the scale level. So one may wonder if:

- the initial database contains enough information to allow generalization?
- there are one or many kinds of generalizations?

It may be assumed that the difficulty and the cost of generalization caused NMAs to put forward only one type of generalized map for a given scale. However, if a flexible and effective means of generalization existed, it would certainly incite them to carry out different kinds of generalizations according to the point of view of the geographic information. Lanza and La Barbera (1993) proved, in this respect, that a water network can be generalized differently, according to the criteria of hierarchy utilized.

This study is mainly confined to the topographic aspect and it focuses on modelling information appropriate or necessary for generalization. But it is certainly vital to increasingly integrate more flexible generalization criteria to represent geographic space in different ways in order to meet all the demands that users may have. As David Mark emphasized:

> Basic research will be needed to test the adequacy of the cartographic data model for representing all aspects and concepts of geographic space (Mark, 1992).

Generalization should be seen as a process allowing us to perform a change in the perception level of geographic data. Precision and geometry changes are no more than consequences of this process. The authors do not claim that definite answers will be found in this paper, rather we have tried to point out issues that seem to be of prior importance.

6.1 Knowledge needed for generalization

6.1.1 Action versus modelling?

When a cartographer generalizes, his/her objective is to maximize the quality of the information preserved: surely, the definition of quality is subjective as the conflicts in space found in the process of generalization will oblige him/her to make choices (e.g. Should spatial localization of features or their shape be a priority? Is it worthwhile to keep a diversity of information and to reduce the number of features or to select only certain themes?). These choices depend on the specification of the product but also on the final scale and the scale reduction factor. When the scale decreases (let us say under 1:15000), the preserved features have to be significantly enlarged in order to make them visible. Numerous spatial conflicts appear and they are essentially resolved by: a reduction in the number of features, a simplification in shape, or moving features around in the densest areas.

The lower the scale, the falser is the location of features and the more their shape is simplified. In other words, computed information is an abstraction of the initial data. The main issue of generalization is to find the characteristics allowing us to abstract the data. It is therefore clear that generalization cannot be performed without a preliminary analysis of semantic and spatial relations of features as well as their geometric characteristics. Every generalization operation should take into account relations and properties whether as a means or as a constraint. This leads to the fundamental question stated in Bjorke and Midtboe (1993): What is information and how can information be measured?

6.1.2 What is to be thought of a rule-based system?

A cartographer uses knowledge. It naturally comes out that a formalization of this knowledge by means of rules (either production rules or Horn clauses) should be convenient for automating the generalization of all types of data. Unfortunately, to date, such attempts have not been satisfactory (Weibel, 1991; Chapter 1, this volume), the main reasons for this failure being among others:

- the knowledge actually used by the cartographer turns out to be difficult to identify, so the rules expressed are either too general (e.g. if a feature is too small, then it can be

omitted) or too specific (e.g. if a lake is too small, then it should be omitted, except if it is part of a set of small lakes close to each other, in which case . . .);
- the mechanism of analogy is often used but it is difficult to integrate into a purely deductive system.

Therefore, rules are not generic enough as:

- they often happen to contain a mixture of topology and semantic notions (e.g. 'connected roads should remain such');
- numerous rules have exceptions which also have their own exceptions. Deep knowledge (Chapter 1) is missing. The inference engine may lead to incoherent results.

As a result, should the idea of formalizing geographic knowledge be discarded in favour of an interactive generalization which is a sort of manual generalization? It seems rather that the present failure is partly due to the fact that the knowledge formalized is ill-adapted to generalization, partly because of a lack of means of evaluating conflicts and identifying spatial relations between objects and geometric properties of objects.

6.1.3 What knowledge is used by the cartographer?

When digital data are used, features and even information describing them tend to be regarded independently. This is due to the fact that only a sequence of points and an identification code are needed to represent features graphically. Interpretation of geometric properties and spatial relations between features can easily be made visually and informally. Thus, these relations do not need to be coded. On the contrary, when generalization is being carried out, the following questions will be posed.

- Insofar as the analysis level is modified, do objects remain the same?
- How can the characteristics of an object or a set of objects be preserved?
- Are the distribution laws of objects identical for two perception levels?

Assuming that basic semantic objects are called objects, it is tempting to express most generic knowledge that the cartographer uses for generalization in the following way.

- If an object is suitable for the targeted analysis level, it should be preserved or created from other objects. The notion of suitability depends on the objectives of the map or on the database to be created, as well as on the role of the object in relation to its neighbourhood. An object may be a representative or a synthesis of a set of objects. It can also be suitable because it acts as a link between two important objects (e.g. a secondary road kept solely because it connects a town with a tourist site).
- The geometry of objects preserved or created should correspond to a new spatial resolution. The preserved objects will have a simplified geometry with the exception of characteristic shapes which will have to be kept or amplified.
- If objects have a mutually important relative position, this relative position should be preserved (e.g. connex objects should remain connex, close objects should remain close).
- The result of every cartographic work should be legible. Thickening due to symbolization, overlapping of neighbouring objects, too great a density of information, too small or too narrow objects, should be avoided.

Therefore, it is indispensable to preserve in the best possible way geometric properties, and spatial and semantic relations in the process of generalization while respecting graphic limitations which depend on symbolization and the new spatial resolution. Thus, if generalization is to be automated it is necessary to satisfy the following conditions.

- Identify properties and relations between objects needed for generalization. These properties and relations include geometric characteristics, topologic and spatial relations and semantic properties. This process has been termed 'Structure Recognition' by Brassel and Weibel (1988).
- Find the best possible formulation and representation of properties.
- Define the means of finding those properties in a set of data.
- Be able to use them in a generalization operation.

6.1.4 What meaning is to be given to complex objects?

The definition of a complex object is not quite clear. It may be considered as a geographic object composed of elementary geographic objects. In a classic Geographic Information System (GIS) comprising the notion of complex objects, it can be seen that, most frequently, a complex object is a combination of simple objects of the same type which, instead of being labelled with one common attribute value, reference a single complex object. Complex objects simplify some queries (e.g. 'spotting road number 7'), but in the process of a data exchange, they are often disposed of and recomputed, if necessary. These objects do not supply any further information to the database, they just contribute to localize information.

Other types of 'static' complex objects showing a combination of simple objects of different types are actually rather rare. They may be considered as the first step towards a multiple representation of data or simply towards a creation of different levels of perception in a classical database.

In the process of generalization, geographic data from one or many databases is used in order to create a new database with its own data schema. Certain objects will be created from a set of objects that will no longer exist. Those objects which could have been considered as complex ones in terms of their ungeneralized database are regarded as elementary objects for the new perception level. In fact, classical complex objects become simple objects during generalization. The only real complex objects that will be required are ephemeral ones and they will be used to describe distribution or geometric characteristics of a set of simple objects (e.g. in establishing a hierarchy of a water network, in configurations of a road network in an urban area, in types of geometric lines, etc.). These 'complex objects' will be defined in section 6.3 by labelling them with more precise names (i.e. geometric objects, structural objects, etc.).

6.2 *Information needs and modelling for generalization*

6.2.1 Geometric properties of objects

Generalization needs

Numerous algorithms for geometric simplification exist and they are basically filtering and/or smoothing algorithms. The problem now consists in the choice of an algorithm and the parameter values which depend on the objects. Since the geometry of objects is not uniform, knowledge of geometric characteristics of each object should render the choice of an algorithm and of its parameter values more sensible (Plazanet *et al.*, 1994).

Frequently, a bandwidth approach is used to decide whether a point of a line should be kept; this method does not take into account the fact that the line is in fact a shape (or is composed of shapes). Numerous experiments have shown that this criterium is insufficient. This was the object of the study by Buttenfield (1991) in which the author emphasizes the importance of analysing the shape of an object before generalizing it: 'Knowledge-based simplification requires that the amount and type of detail in the digital file are defined before the algorithm begins to operate, and that expectations of the amount and type of details that should be retained or eliminated at the reduced scale are also defined'. Identification of characteristic shapes is necessary on different levels of perception. On the whole, one should be able to combine points which are part of a geometrically homogeneous section; then, more locally, it may be necessary to describe the geometry of a characteristic shape. For example, one may have to divide a road into sections with a homogeneous geometry (sinuous sections/straight lines) and then describe each bend of each sinuous section. Besides, it is worth noting that shape maintenance, and the measurements performed in order to assess it, are part of the indispensable evaluation of the generalization result quality.

Description elements

Firstly, it is simpler to describe line features. The essential geometry of a surface feature will thus be grasped by the characteristics of its outline and its skeleton. Further information can be included, such as the identification of elongated or ovoid shapes.

To describe a linear object it should be known whether it is: composed of straight lines, of regular curves or of accidental shapes, composed of characteristic, regularly repeated shapes, or sinuous with a fractal tendency. Concerning its characteristic shapes, do they have: a regular frequency and bandwidth, a prevailing direction, acute or right angles, or cusps or loops according to the prevailing direction of the object?

It may turn out that the vocabulary used to describe a line is often inaccurate and sometimes repetitive. There is a marked tendency to describe the geometry of objects by using a vocabulary related to the nature of the objects represented, e.g. mountain roads, meandering water-streams; this often gives a more precise idea of the general shape but very little spatially localized information.

Geometric modelling

The simplest geometric modelling consists of representing lines by sequences of arranged coordinates $\{(x,y)\}$. A line can also be described by encoding changes in direction (i.e. Freeman encoding chains (Freeman, 1978)) or polar coordinates. These descriptions are insufficient as they do not allow identification of object shapes. The difficulty of finding a better formulation is due to the fact that most topographic objects have a complex or even transcendental shape. Geometric modelling should allow identification of the geometry of a line in the following way:

- globally, in order to use the appropriate algorithm to modify a line as a whole;
- locally, in order to enable the identification of a characteristic shape and its local modification.

Global description of a line

Whether the global description of a line is qualitative or quantitative, analogical or analytical, it may be assumed that identification of characteristics will be made through mathematical means, most of which are relatively simple, such as computations of angles, distances or surfaces. However, numerous problems remain to be solved:

- an identification of line types that allows a complete and non-redundant taxonomy;
- criteria revealing line description;
- the interpretation of classical geometric characteristics (angles, distances, etc.);
- line-splitting methods necessary to define fragments homogeneous in geometry. The Douglas and Peucker algorithm (Douglas and Peucker, 1973) presents obvious limitations in this respect.

The definition of both taxonomy and criteria should be attempted to enable the classification of every line type and the qualification of each line. The solution could consist of defining cartographies of line types according to classical criteria of geometric measurements while taking into account acceptable value variations and problems of similarity. The authors' approach is to investigate possible characterizations and geometric representations and, in parallel, to evaluate classical algorithms on typical feature classes. This point is not developed here, the focus being put on modelling for generalization.

Description and characterization of shapes
The description of local geometry can be based on the identification of characteristic points and a simple mathematical formulation of the geometry of the line between two typical consecutive points. Different analyses have been proposed in the past. They may be classified as follows.

- Techniques which rely on direction changes: Freeman chain encoding (Freeman, 1978) and 'energy' measurements (Williams and Shah, 1992; Bjorke and Midtboe, 1993). The main difficulties in these approaches are to manage problems due to the fact that points are not equidistant, and to divide space into a discrete and significant number of direction zones.
- Fractal analysis: 'The notion of fractal geometry is closely linked with invariance properties through a change in scale' (Gouyet, 1992). Various works have been produced to study the fractal dimension of a line (Dutton, 1981; Buttenfield, 1985; Müller, 1986). It turns out that certain types of natural lines — particularly coastlines — do have a fractal tendency. Such characteristics of the line length are parameters that can be used to qualify a line, or to evaluate results of a smoothing.
- Attempts for global characterization: (Buttenfield, 1985; McMaster, 1987; Buttenfield, 1991; Chapter 12, this volume) have defined criteria for characterizing a line feature or defining its structure signature (for example using strip trees (Ballard, 1981)). The usefulness of these parameters has been proved by the fact that they have enabled the identification of differences in the structure signatures of lines chosen according to intuitive criteria of geometrical homogeneity.
- Detection of characteristic points. Different studies have shown that the identification of characteristic points of a line seems to follow rather objective rules as a varied human population, cartographers and others, select the same points, corresponding to the inflexion points and to the vertices. As a matter of fact, the success of Douglas and Peucker's filtering algorithm may be explained by the fact that the points it selects approximate the line vertices quite well. However, line vertices are not sufficient for characterizing a line. Numerous studies have been made on the utility of the inflexion points and on the different techniques allowing identification of them (e.g. Freeman, 1978; Thapa, 1989; Affholder, 1993).

Work accomplished in the field of artificial vision, which often focuses on curvature extrema (Hoffman and Richards, 1982; Leyton, 1988; Lowe, 1988; Milios, 1989; Rosin and West, 1990; Mokhtarian and Mackworth, 1992; Rosin, 1993a, b), could also provide interesting input for this research axis. We do not consider relief characterization and classification here although it is of prior importance for relief generalization (Weibel, 1987) and closely related to the topics discussed above.

Description by means of mathematical formulation

Intuitively, it may be assumed that the approximation of a set of points by a polynomial function, by using the least-squares method for instance, would allow the identification of line types. In fact, it turns out that, when the number of points to be approximated is large, equations become too complex for identification purposes (Maling, 1968; Buttenfield, 1985). Therefore, appproximations to define local forms will be used while limiting the polynomial degree so as to be able to use and interpret the results.

The idea retained by Affholder (1993) is thus primarily to model man-made topographic objects, such as roads, by using polynomials of the 3rd degree — cubic sections whose equations have the form $y = ax^3$ in a local coordinate system. The reason for satisfactory results in modelling roads by using such cubic curves is that the modelling method has been chosen according to the object to be modelled: the curves used are mathematically a good approximation of the clothoids used by engineers to construct roads. The point is not to find a completely generic modelling method but to find the best simple modelling adapted to a type of feature. At any rate, it can be assumed that man-made features would be easier to model than natural features for which polynomial geometry seems ill-adapted. Nevertheless, it has not been proved that, for these features, polynomial modelling would not contribute any information on characteristic shapes.

6.2.2 Spatial relations

According to Kate Beard, spatial relations between objects present constraints for each generalization operation:

> Structural constraints may be expressed in terms of maximizing, minimizing or maintaining certain relationships. In the spatial domain, distance relationships among objects are fundamental. Both interior dimensions of objects and the spacing between them are relationships which may need to be preserved or in other ways constrained. Other examples of spatial relations include direction, connectedness, containment and adjacency (Beard, 1991).

Spatial relations may be divided into relations of connexity and relations of spatial arrangement.

Connexity relations

Connexity relations should be preserved because they give information on objects which communicate in nature. Moreover, they are necessary in generalization to propagate shifting and deformation between connex objects. Besides, they allow identification of objects which share the same local geometry (e.g. a road fragment and an administrative boundary).

Topology allows expression of relations of inclusion, intersection, and adjacency between objects in a simple way. Planar graphs are often used to model topologic relations in dimension 2. Classical representation consists of memorizing, for each arc, its initial node, its final node, its right and left faces and then, for each face, the set of arcs of which it is composed. This is not the most practical representation, particularly when faces that are not directly defined are to be handled. In addition, this structure does not allow identification and immediate management of topologic objects contained in the faces (isolated nodes, dangling arcs, other faces). Topologic maps are derived from combinatorial maps (Berge, 1983), which are an improvement on the structure of classical graphs by adding a hole handling facility (David, 1991; David *et al.*, 1993). Topologic maps are based on the notion of a *dart* which is an oriented arc with functions allowing movement from one topologic object to another. These functions appear to be a convenient way of handling topologic information.

Spatial arrangement relations

Generalization needs

Proximity relations allow description of the relative location of objects one in relation to another. They contribute in several ways to generalization, the main one being rather vague as it consists of preserving the relative location of one object in relation to other ones. Studies made at the Institute for Aerospace Survey and Earth Sciences — ITC (i.e. generalization of a set of lakes, of a road network in an urban zone) made it clear that, to generalize a set of objects, it was necessary to have a great deal of information on topologic and geometric relations of objects as well as the knowledge of spatial arrangement relations obtained by computing proximity relations. The major difficulty is to preserve the structure of the object spatial distribution (Müller, 1993).

Geometric distribution of objects also allows their identification. Let us consider the generalization of a set of houses. The method consisting of increasing their size in order to make them visible and then aggregating them is unsatisfactory as it will produce erroneous information. It is necessary to preserve the geometric distribution as this will allow identification of the houses and prevent construction of a representation which looks like a set of large buildings. In terms of constraints, it is of vital importance to:

- preserve proximity; and
- preserve the geometric distribution of objects, if it is characteristic.

In terms of tools, proximity relations can be used to:

- detect a proximity conflict (or spatial conflict);
- identify a complex (structural) object;
- eliminate objects if they are part of a set of objects which are of the same nature while preserving the general distribution (structuring operator); and
- aggregate close objects of the same nature.

The problem which remains to be solved is to find out to what extent the same elements of object organization can be found at different scales. In the same way, there are critical scales at which certain objects change in dimension. Identification of spatial distribution of objects would not provide any interesting information beyond that limit. This occurs particularly when there is a significant change in scale (e.g. if a set of buildings is replaced by a single block delimited by neighbouring streets, the geometric distribution of the initial buildings does not contribute any usable information; only the density and the nature of the buildings would provide some relevant information).

Types of spatial arrangement relations

Two objects are neighbours if they are close to each other. Although simple as stated, proximity relations are difficult to use in practice. The objective is to define the way in which objects are close.

The first approach consists in qualifying the relative position of one object in relation to another. First, the positions can be described by using a particular vocabulary defined according to a frame of reference inspired by everyday language: right/left, in front of/behind, in the same place, surrounded by, parallel to. Distance can be combined with such location; it can be known precisely, defined by an interval, or unknown (Freeman, 1978; Mark and Frank, 1989; Donikian *et al.*, 1993).

The second approach is to try to define the geometric distribution of objects by means of geometric structures. Thus, objects may be:

- aligned;
- distributed orderly on a grid or network (hence, the shape of the grid or the type of network should be defined (Argilias *et al.*, 1988); it may be a TIN such as the SDS used in Chapter 8);
- distributed on a particular pre-determined structure (a circular structure with increasing density close to the centre, star-shaped structure, etc.).

Modelling proximity relations

To spot objects potentially in conflict, it is necessary to identify close objects. Many solutions can be envisaged.

- There can be a raster view of the data used, taking into account the span induced by the required symbolization, and then an identification of pixels which correspond to overlaps. The disadvantage of this method is the fact that a differentiation between real intersections and conflicts is rather complex. The problem of computation time and of data volume can also be a shortcoming,
- For each object, a computation of its neighbours is made possible through classical Euclidian methods of distance calculation, while the search for potential neighbours is optimized by means of a spatial index. In this respect, spatial indexes may be classified into classical spatial indexes (regular or recursive division of space, K-D-B tree, Grid file, R-tree, Bang file, etc. (David, 1991; van Oosterom, 1991) and topology-related indexes (Cell trees, Strip tree, Arc tree, Multi-scale line tree or BSP tree (van Oosterom, 1991); also Delaunay triangulations or Voronoï diagrams). The best choice is currently not clear. Whatever the optimization method used, the relevant information to be preserved will be the shortest distance between two objects, together with its location and direction (e.g. {dist; (x_1, y_1); (x_2, y_2)}). A qualitative representation of this information may also prove useful.

Modelling distribution structures

It is clear that there are no two identical geometrical distributions of features in nature. However, the procedure consisting in attempting to categorize distribution structures, aims at reducing their complexity so as to allow an elaboration of rules for simplification purposes of these distributions in the process of a change in scale. Consequently, our objective will be, primarily, to identify similarities in distribution.

The first step is to begin with the intuitive thought that there exist similarities in the geometric distribution of objects of a kind. Thus, searching for structures can be approached by an attempt at identifying distribution types according to objects, though it may later mean trying to define more generic structures. This procedure is feasible insofar as the structure is related to the object and, more generally, to its function. For example, a road network has an exchange function and a form composed of connected ramifications so as to cover space in the best possible way, just like irrigation networks where there is no hierarchy. Relationships between the street network and the distribution of buildings are also of particular interest since the configuration of the street network and settlements are closely related to the type of urban structure. Nevertheless, one may wonder if a unification of structures is possible insofar as the distribution structure and its generalization depend on the nature of the objects.

One of the ways of using structures may consist of defining prototypes of distribution structures, and then in attaching a set of objects to a prototype if certain membership conditions are fulfilled. It would therefore be necessary to permit certain value variations — angle, distance, number of objects — and to find a means of summarizing the result, so as to find out if a set of objects can or cannot be attached to a prototype, and if so, how. In other terms, a prototype can allow a spatial distribution type to be qualified, but its objective is not to describe each distribution precisely.

The main experimental work on prototypes was done on water networks (Argilias *et al.*, 1988) or more generally on natural structures (Wang and Müller, 1993), perhaps because the objects constructed are too diversified to allow for a geometrical structure synthesis. Nevertheless, it can be thought that certain structures are easily recognizable, such as house alignments in a zone which can be defined as a face delimited by a road network in a semi-urban area. A lot of work remains to be done in this area. This will be one of our main research themes, with a focus on complex interchanges, urban street networks and urban building structures.

6.2.3 Semantic relations

Generalization needs

The first stage in generalization consists of a transition from an initial data schema to one corresponding to a new level of perception (see Foreword above). This entails a redefinition of the relevant objects from the initial ones without modifying their geometry (or almost so, as a slight filtering operation may be performed in order to reduce the data volume). Schema generalization operators are (Ruas *et al.*, 1993): classification, aggregation (aggregation of connex objects of the same category and with the same values and attributes), generalization (putting objects into one, more generic, category) and association (computation of new relations between objects). At this stage, properties and semantic relations of objects are essentially used.

The second stage of generalization consists of modifying the geometry of objects so as to solve problems arising from symbolization. Certain conflicts cannot be resolved by a mere transformation of shapes or by displacement. Therefore, certain objects have to be aggregated, others eliminated or changes in dimension have to be made, depending on the context (e.g. San Francisco Bay in Mark (1991)). In all these cases, spatial relations and semantic relations between objects have to be taken into consideration. For example, only objects of the same nature may be aggregated; an object can be preserved because it is representative of a set of objects of the same nature or because it allows connection of objects which should be preserved. In addition, in order to move objects around, the order and the amount of displacement done will depend on the relative number of objects in conflict. So, each object (or object class) should be labelled with a displacement threshold according to the specification of the product to be made.

Types of semantic relations

The relations existing between geographic objects are relations which are defined by users according to their criteria and/or needs. Most relations are those of composition. A complex entity is composed of a set of entities which describe it. For instance, a hospital is composed of a set of buildings and areas. Such a set can be replaced by a single symbol: 'Hospital' in case of conflict or overlapping. There are other relations which often result from commmunication between two objects such as: 'gives access to', 'passes under or over'. Communication relations are important to see if an object is functional (e.g. a road cannot be eliminated if it is the only possible communication between two important objects). Other relations certainly remain to be identified. Those will, no doubt, depend on the product to be made.

Semantic relations modelling

In order to enable correct modelling of objects, the notion of simple and complex objects should be established to handle the coexistence of at least two different descriptions of the geographic world. This is, at least, a convenient if not optimal way of obtaining a double data representation in anticipation of a multiple representation (see section 6.1.4).

Semantic relations are also of essential importance to reduce the number of objects in one category. As a random elimination is not acceptable, the selection method stems either from the definition of criteria of spatial distribution or from the establishment of a hierarchy within a set of objects. From this hierarchy, each object would be given a value summarizing a set of criteria of importance according to the new specifications. In establishing a hierarchy in a set of objects, geometric structures may also be of use. Other criteria based on statistical information (Richardson and Müller, 1991) or on semantically weighted connections (Beard and Mackaness, 1993) have also been proposed; this shows the great variety of available semantic criteria.

6.3 *Suggestions on modelling for generalization purposes*

The aim of formalizing and modelling relations between objects is to facilitate or even make possible the generalizing procedure. This section deals with some methods used for modelling relations described in section 6.2. It is obvious that certain relations or properties are necessary for all objects (such as topologic relations) and that other relations will merely concern a restricted number of objects (e.g. house alignment). What is important is to be able to introduce properties needed for generalization into a data model while being aware of the fact that the need for modelling will be increasing, and its importance will grow together with the progress in automated generalization. The model used should therefore be easily extensible.

6.3.1 Choices in the field of modelling

By the end of 1991 the laboratory Cogit of IGN started research in order to study feasible processes for the generalization of the databases in progress at the institute. At first, it was necessary to conduct a survey on generalization (Ruas *et al.*, 1993) and then to define adequate data modelling which could be used as a basic structure in a rule-based system. Considering the progress in research on generalization and the amount of work to be done, the first step is to keep all options open: appropriate modelling which allows us to resolve the problems of generalization in the best way should be sufficiently flexible and progressive. This essential criterion has incited us to work in an object-oriented way to enable easy improvement of our modelling according to the needs and constraints encountered.

We have attempted to find a structure allowing us to carry information which we consider essential, while incorporating potentially important data even if little work has been done to confirm their pertinency (i.e. geometric structures). A set of objects of the same nature will be called a layer. The following choices were made.

1. The two fundamental groups of objects are geographic objects and topologic objects. Geographic and topologic layers are concerned.
2. A topologic layer contains the geometry of objects. In order to ensure better control of the problem of floating point approximation, the coordinates are integers.
3. Geographic objects are broken down into simple and complex objects. A simple object is related to at least one topologic object. A complex object can be composed of simple and/or complex objects.
4. All simple geographic objects corresponding to the same level of description are related to a unique topologic layer, with the exception of 'contour line objects'.[1] Thus, two geographic objects can, partially or totally, share the same geometry.
5. A topologic layer is based on a division of space into a complete planar graph. Basic topologic objects are inspired by definite objects in the theory of topologic maps. Thus, topologic objects are composed of nodes, darts and faces.
   (a) A node has either an ordered list of darts or has a surrounding face if it is pending.
   (b) A dart has its reversed dart. Each dart points to its right face and to an initial node. A dangling dart has a surrounding face: it is considered as a hole.
   (c) A face has an ordered list of darts and, possibly, a surrounding face and a set of holes.
6. A geometric layer is added to the two basic layers mentioned above. It is intended to host geometric structured primitives (such as cubic curves) which are created for generalization purposes. This layer allows description of the geometry from one or many objects without being limited by topologic relations between objects. For example, it is possible to associate a set of darts with a single geometric primitive of a cubic type or to associate a dart with a set of cubic curves and other geometric primitives to be defined. Thus, in the process of certain geometric modifications (e.g. simplification or moving around) it will be possible to make use of a geometric primitive either as a constraint or as a handy tool. Each geometric modification of a geometric primitive will lead to readjustments in the coordinates at the level of the topologic objects.
7. A structural layer is added to the other layers. This layer should allow for a description of a geometrical distribution of a set of objects. It could be used as a constraint or as a means of handling such things as the selection or displacement of objects (e.g. house alignments). This layer and the previous one are typically layers of ephemeral 'meta-information'.

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[1] Contours are only one possible representation of relief information. They cannot be integrated, as this may result in too great a fragmentation of the basic topologic layer. However, relief should be taken into consideration for the treatment of certain data. For example, to select a water network, one could be led to establish its hierarchy by using altimetric information.

8. The four layers of objects — geographic, topologic, geometric and structural — allow description of a view on geographic data (see Foreword). Such a view will be called world or perception level. The system should contain a minimum of two worlds: that composed of the initial data, called the *world of reference*, and that which is being generalized, called the *active world.* Hence, instead of a set of representational planes associated with each individual feature (Chapter 7), we consider several worlds containing different and related images. The first approach is likely to be better suited for cartographic data storage while the authors think that the latter one is more convenient for generalization purposes.
9. The world of reference is indispensable in controlling the quality of generalization. So, the objects of the active world are linked with objects of the world of reference.
10. In order to enable a visualization of objects according to the computing means used, an extra graphic layer is necessary. Then, topologic objects are linked with graphic objects of visualization. Topologic objects have attributes which are used for deriving the graphical symbolization as well as for calculation of proximity conflicts.
11. In order to optimize proximity computation needed for conflict detection, and to handle displacement, a Quad-tree indexing technique is used. This indexing is also useful for optimization of interactive operations (e.g. mouse pointing).

6.3.2 Implementation

The implementation is based on an expert system shell (Smeci, developed by the company Ilog) which has two interesting characteristics: the inference engine allows it to generate different states and the working memory is object oriented. Thus, it is easy to define categories (object classes of Smeci), and the associated attributes allow storage of descriptive data of each category and establishment of links between objects (e.g. composition relations, topologic relations, etc.). Methods and daemons allowing handling of objects are associated with each category. These methods can be triggered by sending a message (or by an action for reflex methods). The graphic layer is managed by another software package (called Maïda2D), allowing visualization and creation of objects. These graphic objects are not saved during the different sessions. A Maïda object should be considered as a screen image of a topologic object. Each geometric computation or transformation (e.g. distance, displacement, etc.), even if triggered off interactively by means of a Maïda2D object, is computed by using the topologic objects (hence in integer coordinates), and is then sent back to the Maïda2D objects level. Furthermore, Maïda2D provides an integrated Quad-tree index which is useful for the identification of isolated objects which are contained in faces, and for the optimization of distance computation. An interface software package can also be used (Aïda); it allows release of general functions to check data, grasp parameters, etc. A diagram on modelling the active world is shown in Figure 6.1.

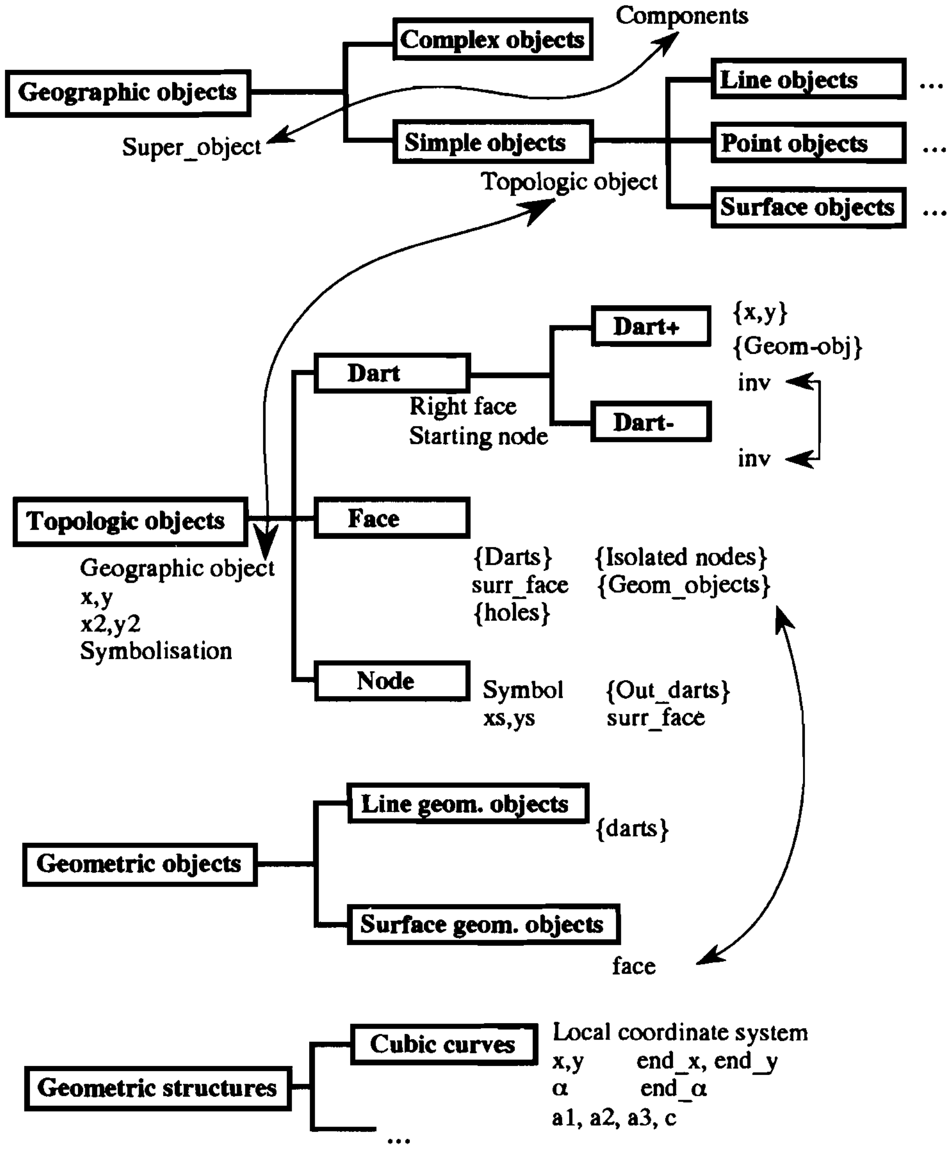

Figure 6.1 Schema of active world.

6.4 Dynamic utilization of modelling for data generalization

It is assumed that the following hypotheses and contexts hold.

- Geometric properties, semantic and spatial relations have been identified and stored in the database by means of objects (e.g. geometric objects and structures) and relations. Point and object filtering have been performed. Data is pre-generalized.
- There are two related object spaces (or worlds): the space of objects to be generalized and the space of reference.
- Objects from the active space are given a simplified symbolization allowing a visualization of overlapping between objects.

It is now time to proceed to identification and to conflict spatial resolution. What is clear is that there is no pre-defined sequence of operations. Most operations triggered off on a set of data without any control would produce violations of relations between objects which would be impossible to correct properly and rapidly. Scale-consistent symbolization, as well as new legibility constraints, will allow identification of conflictual zones. Faced with each area of conflicts, a method of spatial resolution should be identified whose objective would be to minimize the number of conflicts while respecting fundamental constraints. It is obvious that numerous methods of spatial resolution could be envisaged for each conflict. Rules should enable the selection of the best possible methods. The mechanism of state creation and backtracking allow the user to go back to one or many previous states in the case of a deadlock or of an increase in the number of conflicts. Insofar as the objective is to handle only one database, operations will be essentially sequential.

It is already possible to assume that displacement should be controlled from the reference objects and by constraints of global forms.

Studies of the progress at IGN aim at refining data modelling and at analysing optimal utilization of generalization operators as well as their demand in the field of modelling. Table 6.1 shows correlations between classical operators of generalization (i.e. selection, shape simplification, caricature, aggregation, etc.) and data modelling.

6.5 Conclusions

A lot of work has been carried out in the following areas:

- geometric operations and, to a lesser extent, geometry characterization,
- cartographic/generalizing knowledge, but most often limited to 'surface rules' or to narrow domain knowledge bases,
- models of generalization, but which are still far from being implemented.

The authors think that in order to cope with the holistic nature of the generalization process, especially for medium scales, and to develop more general rules, a lot of attention has to be paid to information/knowledge entailed in initial data and which influences generalization decisions.

In this paper the authors have tried to summarize the different information/knowledge categories that can be considered and some possible directions for their representation and use in a generalization process. It is clear that the final word has not been said with

Table 6.1 Generalization operators and object properties and relations

Property operation	Geometry	Connexity	Proximity/inclusions structures	Semantic properties
Selection	T: Elimination of too small objects	T: Selection of objects which implement a connexity link		T: Importance of object depends on their nature
Filtering	C: Maintenance of characteristic local shapes	C: Filtering applied between topologic nodes		
Smoothing	C: Maintenance of characteristic local shapes T: The geometric class dictates the choice	C: No creation of new intersections	C: Relative locations are to be maintained	
Caricature	C: Maintenance of characterstic local shapes T: The geometric class dictates the choice of the algorithm	C: No creation of new intersections	C: Relative locations are to be maintained	
Aggregation	C: Maintenance of characteristic local shapes The geometric class of the resulting object has to be the same as before	C: Topologic changes must be restricted to aggregated objects T: Adjacent objects may be aggregated	C: The new objects must be contained in the same face T: Close objects may be aggregated	C: Objects of similar nature may be aggregated T: Components of a complex object can be aggregated
Structuration or typification		C: Topology must be maintained	T: The structure is represented and generalized	C: Objects of close nature may belong to the same structure
Cusp/collapse	T: Detection of small objects	C: Topology update	C: Update of structure of proximity relations	T: Definition of applicable symbolization
Enlargement	C: Maintenance of characteristic local shapes T: Detection of small objects	C: No new intersections	C: The enlarged object must remain in the same face	
Displacement	C: Maintenance of characteristic global shapes T: Irregular shapes have to be moved first	C: Angles of intersections must be maintained T: Propagation throughout the network	C: Maintenance of distribution structures T: Propagation on close objects	C: Important objects are displaced by others

T: Relation/property is used as a tool.
C: Relation/property acts as a constraint.

respect to these issues but, still, our claim is that it is possible to implement some of these ideas provided that the development environment is flexible and extensible enough to allow for further additions and refinements. The system under development, based on an OO and KB shell, already incorporates a significant part of the ideas expressed in this paper.

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