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Generalising spatial data and dealing with multiple representations

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Functions for generalising spatial data are of fundamental importance in GIS because of a variety of requirements for scale-changing as well as thematic reduction and emphasis. Following a brief introduction, section 2 discusses what generalisation is, what its objectives are, and why it is important. In section 3, the distinction is developed between process-oriented and representation-oriented approaches to generalisation, first discussing the latter in the context of multiple representations and multi-scale databases. Section 4 provides an introduction to the range of conceptual models of process-oriented generalisation, outlining the nature and relationships of data models, operators, objectives, and controls. Section 5 sketches the requirements for a successful digital generalisation system, including elements of data modelling, structure and shape analysis, generalisation algorithms, knowledge-based methods, human-computer interaction, and quality evaluation. The chapter concludes with a brief look at some operational generalisation systems, recently developed and still evolving.

1 INTRODUCTION

'Wherever there is life, there is twist and mess: the frizz of an arctic lichen, the tangle of brush along a bank, the dogleg of a dog's leg, the way a line has got to curve, split or knob. The planet is characterised by its very jaggedness, its random heaps of mountains, its frayed fringes of shore . . . Think of a contour globe, whose mountain ranges cast shadows, whose continents rise in bas-relief above the oceans. But then: think of how it really is. These heights aren't just suggested; they're there . . . What if you had an enormous globe in relief that was so huge it showed roads and houses – a geological survey globe, a quarter of a mile to an inch – of the whole world, and the ocean floor! Looking at it, you would know what had to be left out: the free-standing sculptural arrangement of furniture in rooms, the jumble of broken rocks in a creek bed, tools in a box, labyrinthine ocean liners, the shape of snapdragons, walrus . . . The relief globe couldn't begin to show trees, between whose overlapping boughs birds raise broods, or the furrows in bark, where whole creatures, creatures easily visible, live out their lives and call it world enough.' (Dillard 1974: 141–3)

A Highway Department studies how to widen and straighten a road that runs through towns and villages in a river valley. A property owner decides to develop land that has restrictions by the state on construction within 100 metres of waterways. A planning board attempts to rationalise a community's haphazard zoning code to minimise future conflicts between adjacent land uses. A farmer buys a new, larger tractor and needs to revise how he or she ploughs and intercrops in hilly terrain.

All of these are real-world analogues of what cartographers call map generalisation. Although they concern physical forms and processes on the landscape, these decisions also involve abstractions familiar to users of GIS, such as categorical coverages, curve geometries, proximity buffers, and spatial autocorrelation. Were the people described above to make use of GIS to help solve their problems, they would quickly see that in making and manipulating 2-dimensional representations of their project worlds they would be making cartographic decisions, and furthermore that their systems would not be of very much help in the process.

This chapter describes what generalisation of spatial data is, why it is necessary, some techniques for performing it in the digital domain, and what tools currently exist to support it, providing pointers to some of the recent research literature. More detailed surveys of generalisation techniques have been published, notably by McMaster and Shea (1992) and Weibel (1997), who focus on algorithmic methods. This topic is discussed from the perspective of data quality by Veregin (Chapter 12). Compilations of recent research are provided by Buttenfield and McMaster (1991), McMaster (1989), Molenaar (1996a), Müller et al (1995), and Weibel (1995a). For discussions of generalisation in the context of particular applications see, for example, Larsen (Chapter 71), Meyers (Chapter 57), Wilson (Chapter 70), and Yeh (Chapter 62).

2 DESCRIBING GENERALISATION

Our world presents us with an infinite regress of detail having neither beginning nor end. Digital computers, being primitive machines with limited memory for and no real understanding of facts, must be coaxed and prodded artfully to do anything useful with data describing the planet, its regions and phenomena. As Dillard thoughtfully observes, if we try to model the world it is impossible not to generalise spatial data, whether we intend doing so or not.

2.1 Generalisation in conventional cartography

In conventional cartography, map generalisation is responsible for reducing complexity in a map in a scale reduction process, emphasising the essential while suppressing the unimportant, maintaining logical and unambiguous relations between map objects, and preserving aesthetic quality. The main objective then is to create maps of high graphical clarity, so that the map image can be easily perceived and the message the map intends to deliver can be readily understood. This position is expressed by the concise definition which equates map generalisation to 'the selection and simplified representation of detail appropriate to the scale and/or the purpose of a map' (ICA 1973: 173).

Scale reduction from a source map to a target map leads to a competition for space among map features caused by two cumulative effects: at a reduced scale, less space is available on the map to place symbols representing map features, while at the same time, symbol size increases relative to the ground it covers in order to maintain size relations and legibility. Figure 1 illustrates the spatial conflicts that arise from reduction of available map space and enlargement of symbol sizes. These can be resolved by simplifying symbolism, by selecting only a subset of features to depict, and by displacing some features away from others (e.g. moving buildings away from streets).

However, note that map scale is not the only factor that influences generalisation. Map purpose is equally (and perhaps even more) important. A good map should focus on the information that is essential to its intended audience. Thus, a map for cyclists will emphasise a different selection of roads than a map targeted at car drivers. Map purpose also influences

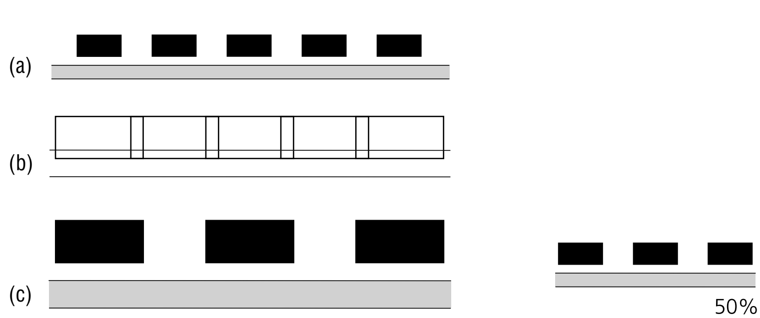


Fig 1. Competition for space among map features as a consequence of scale reduction.

directly the selection of the appropriate map scale, as spatial phenomena and processes should be studied at the level of scale at which they are most relevant (Dikau 1990). Other factors that control traditional map generalisation are the quality of the source material, the symbol specifications (e.g. the width and colour of line symbols to depict roads, political boundaries, etc.), and technical reproduction capabilities (SSC 1977). The combination of these factors is termed the 'controls of generalisation'.

2.2 Generalisation in digital systems

In digital cartographic systems and GIS, generalisation has gradually assumed an even wider meaning. It can be understood as a process which realises transitions between different models representing a portion of the real world at decreasing detail, while maximising information content with respect to a given application. Figure 2 shows how transitions take place in three different areas along the database and map production workflow; the terminology used here was originally developed for the German Amtliches Topographisch–Kartographisches Informations system (ATKIS) project (Grünreich 1992), but has since been adopted by other authors. Generalisation takes place:

- as part of building a primary model of the real world (a so-called digital landscape model or DLM) – also known as object generalisation;
- as part of the derivation of special-purpose secondary models of reduced contents and/or resolution from the primary model – also known as model generalisation (also termed 'model-oriented', or statistical (database) generalisation by different authors; cf. Weibel 1995b);
- as part of the derivation of cartographic visualisations (digital cartographic models or DCMs) from either primary or secondary models – commonly known as cartographic generalisation.

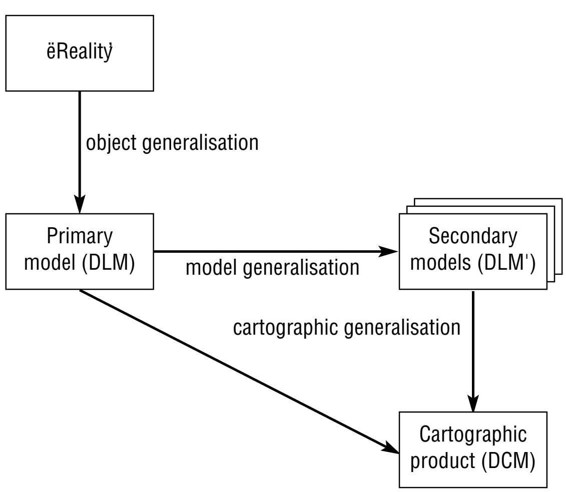


Fig 2. Generalisation as a sequence of modelling operations (after Grünreich 1985).

The next section takes a closer look at the scope and the objectives of these three generalisation types.

2.2.1 Object generalisation

This process takes place at the time of defining and building the original database, called the 'primary model' in Figure 2. Since databases are abstract representations of a portion of the real world, a certain degree of generalisation (in the sense of abstraction, selection, and reduction) must take place, as only the subset of information relevant for the intended use(s) is represented in this database. Although seen from the perspective of generalisation here, this operation is sufficiently explained by methods of semantic and geometric data modelling (which define the relevant object classes and their attributes and relations), as well as sampling methods (which define the sampling strategy and desired resolution and accuracy), combined with human interpretation skills (e.g. if photogrammetric data capture is used: see Dowman, Chapter 31).

2.2.2 Model generalisation

While the process of object generalisation had to be carried out in much the same way when preparing data for a traditional map, model generalisation is new and specific to the digital domain. In digital systems, generalisation can affect directly not only the map graphics, but also the map data. The main objective of model generalisation is controlled data reduction for various purposes. Data reduction may be desirable to save storage and increase the computational efficiency of analytical functions. It also speeds data transfer via communication networks. It may further serve the purpose of deriving datasets of reduced accuracy and/or resolution. This capability is particularly useful in the integration of datasets of differing resolution and accuracy as well as in the context of multi-resolution databases (Goodchild and Longley, Chapter 40). While model generalisation may also be used as a preprocessing step to cartographic generalisation, it is important to note that it is not oriented towards graphical depiction, and thus involves no artistic, intuitive components. Instead, it encompasses processes which can be modelled completely formally (Weibel 1995b); these may, however, have aesthetic consequences for subsequent cartographic generalisation.

2.2.3 Cartographic generalisation

This is the term commonly used to describe the generalisation of spatial data for cartographic visualisation. It is the process most people typically think of when they hear the term 'generalisation'. The difference between this and model generalisation is that it is aimed at generating visualisations, and brings about graphical symbolisation of data objects. Therefore, cartographic generalisation must also encompass operations to deal with problems created by symbology, such as feature displacement (cf. Figure 1), which model generalisation does not. The objectives of digital cartographic generalisation remain basically the same as in conventional cartography (see above). However, technological change has also brought along new tasks with new requirements (Kraak, Chapter 11) such as interactive zooming, visualisation for exploratory data analysis, or progressively adapting the level of detail of 3-dimensional perspective views to the viewing depth. The concept of cartographic generalisation thus needs to be extended. On the other hand, typical maps generated in GIS are no longer complex multi-purpose maps with a multitude of feature classes involved, but rather single-purpose maps consisting of a small number of layers. Furthermore, maps and other forms of visualisations are often presented by means of a series of different partial views in a multi-window arrangement, particularly in exploratory data analysis (Anselin, Chapter 17). Together with the capabilities of interactive direct manipulation these new forms of cartographic presentations partially alleviate (but by no means eliminate) some of the generalisation problems, or at least make them less salient for many GIS users.

2.3 Motivations for generalisation

The discussion above has already alluded to some of the reasons for generalisation. Extending Müller's (1991) discussion of requirements for generalisation, it is possible to develop a more detailed list of motivations.

1 *Develop a primary database*: build a digital model of the real world, with the resolution and content appropriate to the intended application(s), and populate it (object generalisation):
   - select objects;
   - approximate objects.

2 *Use resources economically*: minimise use of computing resources by filtering and selection within tolerable (and controllable) accuracy limits:
   - save storage space;
   - save processing time.

3 *Increase/ensure data robustness*: build clean, lean, and consistent spatial databases by reducing spurious and/or unnecessary detail:
   - suppress unneeded high-frequency detail;
   - detect and suppress errors and random variations of data capture;
   - homogenise (standardise) resolution and accuracy of heterogeneous data for data integration.

4 *Derive data and maps for a range of purposes*: from a detailed multi-purpose database, derive data and map products according to specific requirements:
   - derive secondary scale and/or theme-specific datasets;
   - compose special-purpose maps (i.e. all new maps);
   - avoid redundancy, increase consistency.

5 *Optimise visual communication*: develop meaningful and legible visualisations:
   - maintain legibility of cartographic visualisations of a database;
   - convey an unambiguous message by focusing on main theme;
   - adapt to properties of varying output media.

Examination of the above list reveals that classical cartographic generalisation mainly relates to task 5 (visual communication) and to a lesser extent also to task 4, while tasks 1 to 3 are more specific to the digital domain (object generalisation, model generalisation). In task 5, an aspect of cartographic generalisation germane to a GIS environment is that output may be generated for media of varying specifications, such as high-resolution plotted maps or low-resolution CRT (cathode ray tube) views, requiring consideration of the resolution of the output media when composing maps for display (Spiess 1995).

3 GENERALISATION AND MULTIPLE REPRESENTATIONS

3.1 Generalisation: process-oriented vs representation-oriented view

The above discussion has implicitly taken a process-oriented view of generalisation, understanding it as the process of transforming a detailed database into a database or map of reduced complexity at arbitrary scale. As was already mentioned, generalisation is a complex process, and indeed, satisfactory implementations of all the transformation operations (and their interactions) necessary to achieve comprehensive automated generalisation largely remain to be developed.

An alternative – or complementary – approach is to develop multi-scale databases. We term this approach the 'representation-oriented view', because it attempts to develop databases that integrate single representations at different fixed scales into a consistent multiple representation. An example may help to illustrate the concept. Consider a set of four maps of the same region, drawn at scales 1:1000, 1:25 000, 1:100 000, and 1:250 000. In a particular settlement, dwellings may be represented by their detailed footprints at 1:1000. At 1:25 000 buildings are now represented by simplified rectangular shapes; some building polygons may even have been aggregated. At the next smaller scale, 1:100 000, built-up areas are depicted as tinted blocks defined by the street network and urban boundaries, thus are transformed into larger, less regular polygons. Finally, the 1:250 000 scale map shows only aggregations of blocks, tinting entire cities as one polygonal feature, and transforming smaller towns into point symbols. At still smaller scales, all settlements might be depicted as point symbols. Were all of these maps to be digitised into a GIS, some way would be needed to encode and associate these transformations, in which features group together, acquiring different topologies as well as new symbolism. There are still many open problems regarding how such representational issues should be handled. This section reviews some of the pertinent research efforts, but starts by examining the concept of multiple representations.

Analogous to the concept of views in tabular databases, the term 'multiple representations' is sometimes encountered in discussions of spatial databases (Buttenfield and DeLotto 1989; Devogele et al 1997; Kidner and Jones 1994). It is used to describe a number of different things, including alternative graphical depictions, scale-filtered versions of digital data, changes in database schema, and hierarchical data structures. Multiple representations are often associated with specific display scales, but also may tailor data to serve particular thematic or analytic purposes. In both respects they are intimately related to generalisation.

The most common form of multiple (scale) representations are topographic map and navigational chart series. National mapping agencies and private map producers normally publish maps at different scales, whereby each scale serves as a basis for the compilation of the next smaller one, forming a map series. When map series are updated, usually the large-scale representations are modified first, then the changes are propagated manually through the other scales. In describing the difficulties this entails, Charles Schwarz of the US National Ocean Service wrote:

'The problem of multiple representations is that it is difficult to maintain consistency. One of the most important concepts in database management is that it is preferable to keep only a single copy of a data item, so that consistency is automatically insured. The alternative is controlled redundancy, where one attempts to exercise control procedurally. This is difficult to enforce.' (quoted in Buttenfield and DeLotto 1989: 77)

3.2 Implicit multiple representations: generalisation by preprocessing

Several methods to deal with 'controlled redundancy' – that is, to enable consistent matching of features between different levels of scales – have been proposed. One possible approach is to preprocess the spatial data and compute and store the results of generalisations from a single database for subsequent interactive on-the-fly retrieval across a range of scales. A series of implicit ('latent') multiple representations is thus stored and the need for explicit representations of scale transitions avoided. Oosterom (1993) and Oosterom and Schenkelaars (1995) describe a set of 'reactive data structures' to accomplish this using the object-oriented DBMS Postgres to store spatial data, indices, and procedures (see also Oosterom, Chapter 27). One data structure, the binary line generalisation (BLG) tree, encodes results from Douglas-Peucker line simplification (Douglas and Peucker 1973) to allow retrieval of linear objects at any level of precomputed detail. Another structure, the Reactive tree (based on R-trees), stores collections of points, polylines, and polygons indexed by minimum bounding rectangles (MBR) and by some measure of their 'importance' such as perimeter or area. When zooming in or out, a roughly constant number of objects is selected for display according to their importance. The third data structure, the GAP-tree, is called upon to fill the gaps between regions caused by omitting less important areas. The GAP-tree contains (precomputed) alternative topologies for the omitted polygons by merging the areas they cover with a similar or dominant (most important) neighbour. The importance of an area can, for instance, be expressed as a function of its size and an application-specific weighting factor (e.g. an urban area may be more important than a grassland area). Note that this approach requires complete topology for all areal features to be known in order to build the GAP-tree, as well as extensive analysis and preprocessing of all geometric data. For further details, see Oosterom (Chapter 27).

3.3 Explicit multiple representations: multi-scale databases

Rather than deriving implicit multiple representations by preprocessing, one might wish to build multiple representations by integrating existing mono-scale representations and by modelling explicitly the transitions between scales. According to Devogele et al (1997), the design of such multi-scale databases entails three types of problem:

1 *Correspondence between abstractions*: database schemata translate phenomena of the real world into abstracted instances of databases, by focusing only on relevant parts of these phenomena; integration of abstractions thus requires methods for schema integration on the semantic level.

2 *Correspondence between objects of different representations*: data models are required to describe the links between corresponding objects of the different representations.

3 *Defining the matching process between objects*: in order to identify corresponding (homologous) objects, two sets of geographical data must be searched for objects that represent the same real-world objects; methods for this purpose are subsumed under the term 'data matching'.

Devogele et al (1997) concentrate on the first and last problems, schema integration and data matching. In their research, they aim at developing methods for building a multi-scale database from two road databases available at the French Institut Géographique National (IGN), BDCarto and GéoRoute, for purposes of road navigation. While the first database relates to a mapping scale of 1:100 000, the second contains more detailed road data for urban areas. Since the two databases employ different definitions of feature classes and their attributes, schema integration is required in a first step to arrive at a common schema that allows the two individual schemata to be related and the feature classes matched. In a second step, the individual objects of the two databases are matched, involving the matching of entire roads, as well as individual crossroads and sections. Road matching is achieved by comparing semantic information (attributes such as road number), and crossroad matching by a combination of topological and metric criteria. Section matching is carried out in two steps: first by semantic criteria (sections belonging to the same road are identified), and second by a metric search using the Hausdorff distance (for a definition of Hausdorff distance see, for example, Huttenlocher et al 1992).

A significant part of the research on multi-scale databases has focused on the second of the above problems, the design of data models and data structures to encode the correspondence relations between the individual representations. Most of the work was inspired by the largely hierarchical nature of transitions between scales. Extending a classification proposed by Beard (1991), such hierarchical relations can be found in four fundamental data domains: the domains of spatial primitives (geometric components of entity abstractions, such as points, lines, and polygons); features (real-world referents, such as buildings, rivers, and political units); attributes; and the spatial domain.

In the *primitive domain*, emphasis of hierarchical multiple representations is on the manipulation of detail of spatial primitives. Examples include the BLG-tree described above (Oosterom 1993) and the equivalent 'simplification tree' of Cromley (1991), both of which precompute the order of disappearance of vertices on a line using the Douglas-Peucker line simplification algorithm. In the *feature domain*, a great variety of hierarchies exist which lend themselves to multiple representations.

Sets of features can nest within one another, for example political territories or census geography. Network data, particularly hydrography and roads, may also be classified hierarchically, by ordering stream segments (Rusak Mazur and Castner 1990) and designating routes (Ruas 1995a). A related technique is to identify containment relations between smaller and larger features. For instance, a set of buildings can be represented by a centroid of a block or other feature that contains them. Features can also be grouped into 'placeholders' (e.g. a group of buildings that is turned into a single building or a polygon representing a built-up area at a smaller scale). Timpf and Frank (1995) have proposed the use of a directed acyclic graph to represent such transitions. In the attribute domain, the classical example of hierarchies is categorical data which may have inherent hierarchy, such as land-use or soil classifications. Such inherent relations can be formalised for storage and retrieval as hierarchies (Molenaar 1996b; Richardson 1994). Finally, in the spatial domain, a number of space-primary data structures can be used to represent spatial objects at varying levels of resolution, including quadtrees (Samet 1990), pyramids, and spherical quadtrees (Dutton 1989, 1997; Fekete 1990; Goodchild and Yang 1992). The use of such data structures in generalisation is discussed in more detail in section 5.2.

Clearly, the hierarchy levels used to represent spatial objects in the four domains must be in harmony to achieve a good generalisation. For instance, when feature and attribute hierarchies are used to reduce detail by reducing the number of objects, the primitives that make up these objects must also be simplified. None of the existing techniques for representing multi-scale relations has undertaken to address the hierarchies in all four domains comprehensively, yet examples of a combined treatment of hierarchies exist. The combination of the BLG- and GAP-trees documented by Oosterom and Schenkelaars (1995) allows hierarchies to be linked in the primitive and feature domains (cf. section 3.2). A prototypical GIS that links the hierarchies in the primitive, feature, and attribute domains has been described by Kidner and Jones (1994). This testbed employs an object-oriented database (OODB), as well as object-oriented programming (OOP) techniques, to construct class hierarchies of objects and methods that allow variants of cartographic elements to be stored, manipulated, and accessed for query and display. The system is intended to handle multi-source, multi-scale, and multi-temporal versions of spatial data, incorporating processing histories and other metadata specific to point sets, polylines, polygons, triangulated irregular networks (TINs), and raster images managed by the GIS. An enhancement of this system, now named GEODYSSEY (Jones et al 1996), relies more heavily on metadata and assertions about spatial relations to match multiply-represented features, both exactly and probabilistically. The system can determine if two representations are similar enough to delete one, and will invoke simplification procedures to satisfy queries to which the feature database provides no suitable match. Topological relations and assertions are respected, and can be derived from geometry if necessary.

Finally, while it is easy to find evidence of hierarchical relationships between multiple scales, it is also true that features can change their shape gradually between scales, making it unfeasible to model such transitions in a purely hierarchical fashion. To deal with smooth shape modifications and displacements, Monmonier (1991) has described methods for interpolating (linear) features from two or more representations digitised at different scales, conflated to match corresponding critical points along them. Recently, some GIS vendors have added rubber sheeting tools to their systems; these are primarily designed for map conflation (e.g. for building transportation databases), but may also have applications in the realm of map generalisation.

3.4 Multiple representations of terrain

Terrain surfaces are an important component of many GIS applications, and the need often arises to simplify their structures for analysis or display. Until recently, most digital terrain models (DTMs) were elevation grids having fixed resolution. Many environmental modelling applications utilise such data, which may be resampled to suit the scales and purposes of inquiry. But as Dikau (1990) observes, different types of geomorphological complexity and processes exist at different scales, and all cannot easily be captured in a single DTM, and may be obscured due to resampling operations. Most non-raster-based GIS model terrain using triangular irregular networks (TINs). The requirement to construct TINs at different resolutions is as common as it is for handling planimetric data. A number of solutions have been proposed for the analytic construction of multi-resolution TINs (De Floriani and Magillo, Chapter 38). Early methods for building hierarchical triangulations (De Floriani et al 1984) started with a coarse triangulation of highly significant points such as local extremes, to which less significant points are progressively inserted to yield finer levels of resolution, subdividing the initial triangles while maintaining their edges. This approach allows the hierarchical TIN to be represented as a tree structure, but a problem is that skinny triangles may be formed: this may be alleviated to some extent by using more sophisticated splitting rules (Scarlatos and Pavlidis 1991), or by employing the Delaunay criterion (Boots, Chapter 36) when subdividing coarser triangles (De Floriani and Puppo 1995). As triangle edges of coarser levels of the hierarchy remain unchanged, however, skinny triangles may still form and show up as distinct artefacts on surface displays (De Floriani and Puppo 1995). Such adverse effects can only be avoided effectively by optimising the triangulation independently at each level of resolution (e.g. by constructing a full Delaunay triangulation at each level). This implies a departure from the simple tree structure and building more complex directed acyclic graphs (Berg and Dobrindt 1995), but the surface will be approximated more consistently at each individual level.

One problem that hierarchical TINs must overcome is the elimination of vertical discontinuities that occur when new vertices are added along edges of a coarser triangulation. This necessitates retriangulation in the vicinity of the added points and complicates data management. An alternative approach, called 'implicit TINs' (Jones et al 1994), attacks this problem by not storing any triangles at all; instead, each surface-specific point is labelled with a detail level. This parameter may be derived in a number of ways, most commonly via a full triangulation from which the least significant vertical deviations are identified and these vertices successively removed. When a surface having a certain degree of detail is required for use, all points with greater or equal importance to the criterion are retrieved and triangulated, on the fly, by a Delaunay triangulation which takes into account linear constraints such as surface breaklines (constrained Delaunay triangulation). As constrained Delaunay triangulation is a relatively fast operation (especially when points are spatially indexed), this just-in-time approach to generating multiple terrain representations is more flexible than hierarchical TINs and may prove workable in a number of applications. Similar implicit or online techniques have been presented by Puppo (1996) and Misund (1997) to build TINs of variable resolution. Variable resolution TINs are needed, for instance, in flight simulation where resolution decreases with increasing viewing distance or in other applications where some regions may be in the focus of interest while others are not (Misund 1997).

4 CONCEPTUAL MODELS OF GENERALISATION

Following the discussion of multiple representations in the previous section, the remainder of this chapter will adopt again the process-oriented view of generalisation. To that end, it first examines the models that have been developed in the literature to describe conceptually the processes necessary to derive generalised datasets or visualisations from detailed databases.

4.1 Conceptual frameworks of the generalisation process

In order to understand, much less to render, a complex and holistic process such as generalisation amenable to automation, conceptual frameworks need to be developed. Such theoretical models must be capable of describing the overall process and must at the same time identify essential process components and steps. McMaster and Shea (1992) review several conceptual frameworks proposed in the literature, and then go on to present a comprehensive model of digital generalisation which extends a similar framework proposed by Brassel and Weibel (1988), specifying details for model components which were previously defined only in general terms. The model of McMaster and Shea summarised in Figure 3 decomposes the overall process into three operational areas: first, consideration of the philosophical objectives of why to generalise; second, cartometric evaluation of the conditions which indicate when to generalise; and third, selection of appropriate spatial and attribute transformations which provide techniques on how to generalise. Resolving generalisation is then seen as an attempt to answer each of the three questions in turn, whereby each one forms a prerequisite for the subsequent one.

Digital generalisation

Philosophical objectives (Why to generalise)

Theoretical elements
reducing complexity
maintaining spatial accuracy
maintaining attribute accuracy
maintaining aesthetic quality
maintaining a logical hierarchy
consistently applying rules

Application-specific elements
map purpose and intended audience
appropriateness of scale
retention of clarity

Computational elements
cost effective algorithms
maximum data reduction
minimum memory/storage usage

Cartometric evaluation (When to generalise)

Geometrical conditions
congestion
coalescence
conflict
complication
inconsistency
imperceptibility

Spatial and holistic measures
density measurements
distribution measurements
length and sinuosity measures
shape measures
distance measures
Gestalt measures
abstract measures

Transformation controls
generalisation operator selection
algorithm selection
parameter selection

Spatial and attribute transformations (How to generalise)

Spatial transformations
simplification
smoothing
aggregation
amalgamation
merging
collapse
refinement
exaggeration
enhancement
displacement

Attribute transformations
classification
symbolisation

Fig 3. The conceptual framework of digital generalisation by McMaster and Shea (1992).

The discussion of the philosophical objectives (why to generalise) of McMaster and Shea (1992) uses similar arguments to the ones raised in our review of motivations for generalisation above.

The second area of the McMaster and Shea model, cartometric evaluation (when to generalise) is essentially equivalent in scope to the key steps in the framework of Brassel and Weibel (1988), called structure recognition and process recognition. *Spatial and holistic measures* are employed to characterise the shape and structure of the source data by quantifying the density of feature clustering, the spatial distribution of features, the length, sinuosity, and shape of features, and more. These measures then serve as parameters in evaluating whether critical *geometrical conditions* are reached which trigger generalisation, such as congestion (crowding) of map objects, coalescence of adjacent objects, conflicts (e.g. overlap), imperceptible objects (e.g. objects that are too small to be clearly visible), etc. Process recognition, as specified in the Brassel and Weibel model, is served by *transformation controls* to help select appropriate operators, algorithms, and parameters to resolve the critical geometrical conditions. Points not explicitly mentioned in the McMaster and Shea model, but which are nonetheless of utmost importance to generalisation, are the identification of topological, semantic, and proximity relations, as well as the establishment of priority orderings among features. Examples of cartometric evaluation and structure recognition are provided in section 5.3.

Finally in the third area, spatial and attribute transformations (how to generalise) consisting of a list of 12 *generalisation operators* are identified (originally proposed in an earlier paper by Shea and McMaster in 1989), subdivided into ten operators performing spatial transformations – simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, exaggeration, enhancement, and displacement – and two operators for attribute transformations – classification and symbolisation. The definition of a useful set of operators is of particular interest in the conceptual modelling of generalisation, and deserves further discussion in the following two sections.

4.2 Generalisation operators

The overall process of generalisation is often decomposed into individual sub-processes (Hake 1975). Depending on the author, the term 'operator' may be used, or other terms such as 'operation' or 'process'. Cartographers have traditionally used terms such as 'selection', 'simplification', 'combination' and 'displacement' to describe the various facets of generalisation, an example of which is the definition of generalisation by the ICA (1973) given in section 2.1. A detailed list of terms occurring in traditional cartography has been provided by Steward (1974). In the digital context, a functional breakdown into operators has obviously become even more important, as it clarifies identification of constituents of generalisation and informs the development of specific solutions to implement these sub-problems. Figure 4 illustrates some of the generalisation operators used in the discussion of section 4.3 (Table 1) for a simple map example. Three levels of scale are shown, each one at 100, 50 and 25 per cent, respectively. The appropriate reduction is highlighted by a double frame. Naturally, given the holistic nature of the generalisation process, this reductionist approach is too simple, as the whole can be expected to be more than just the sum of its parts, but it provides a useful starting point for understanding a complex of diffuse and challenging problems.

Shea and McMaster's (1989) typology is the first detailed one which also attempts to accommodate the requirements of digital generalisation, and spans a variety of data types including point, line, area, and volume data. Still, closer inspection of this set of operators reveals that some fundamental operators are missing (e.g. selection/elimination) and that the definitions of some operators are perhaps not sufficiently clear (e.g. refinement) or overlapping (aggregation, amalgamation, merging). Even worse, cartographers may use different definitions for the same term or use different terms for the same definition, as a recent study by Rieger and Coulson (1993) has shown. This has led other authors (e.g. Plazanet 1996; Ruas and Lagrange 1995) to extend this classification by adding operators and by refining definitions of existing ones. The composition of a comprehensive set of generalisation operators is still the subject of an ongoing debate; it is hoped that having it would assist the development of adequate generalisation algorithms as well as their integration into comprehensive workflows.

No matter what set of operators is defined, however, the relationship between generalisation *operators* and generalisation *algorithms* is hierarchical. An operator defines the transformation that is to be achieved; a generalisation algorithm is then used to implement the particular transformation. This also implies that operators are independent of a particular data model (e.g. vector or raster). Algorithms are linked to a specific representation, usually the one that is best suited to implement an operator for a given purpose. For most operators, a number of algorithms with different characteristics have been developed. In particular, a wide range of different algorithms exists for line simplification in vector mode. Note also that operators often are phenomenon-specific, as Figure 5 shows. Generalisation algorithms may be phenomenon-specific and must take into account the particular shape properties and semantics of the real-world features in producing a generalised version. Also, the selection of operators will vary depending on the feature classes and scales.

4.3 Relations between operators, data, and generalisation objectives

Available conceptual models of cartographic generalisation such as the ones referred to above tend to stop short of describing how different operators come into play for map elements and specific purposes. This section attempts to synthesise some of these concepts, illustrating how generalisation operators (procedures), operands (data), and objectives relate to one another.

We have attempted to integrate the diverse and often conflicting operator sets proposed in the literature into a combined list (Table 1). Note that this typology is solely meant to support our discussion and is not intended as yet another proposal of the ultimate set of generalisation operators. There is, for instance, some debate over whether a distinction should be made between simplification (by weeding redundant points from a

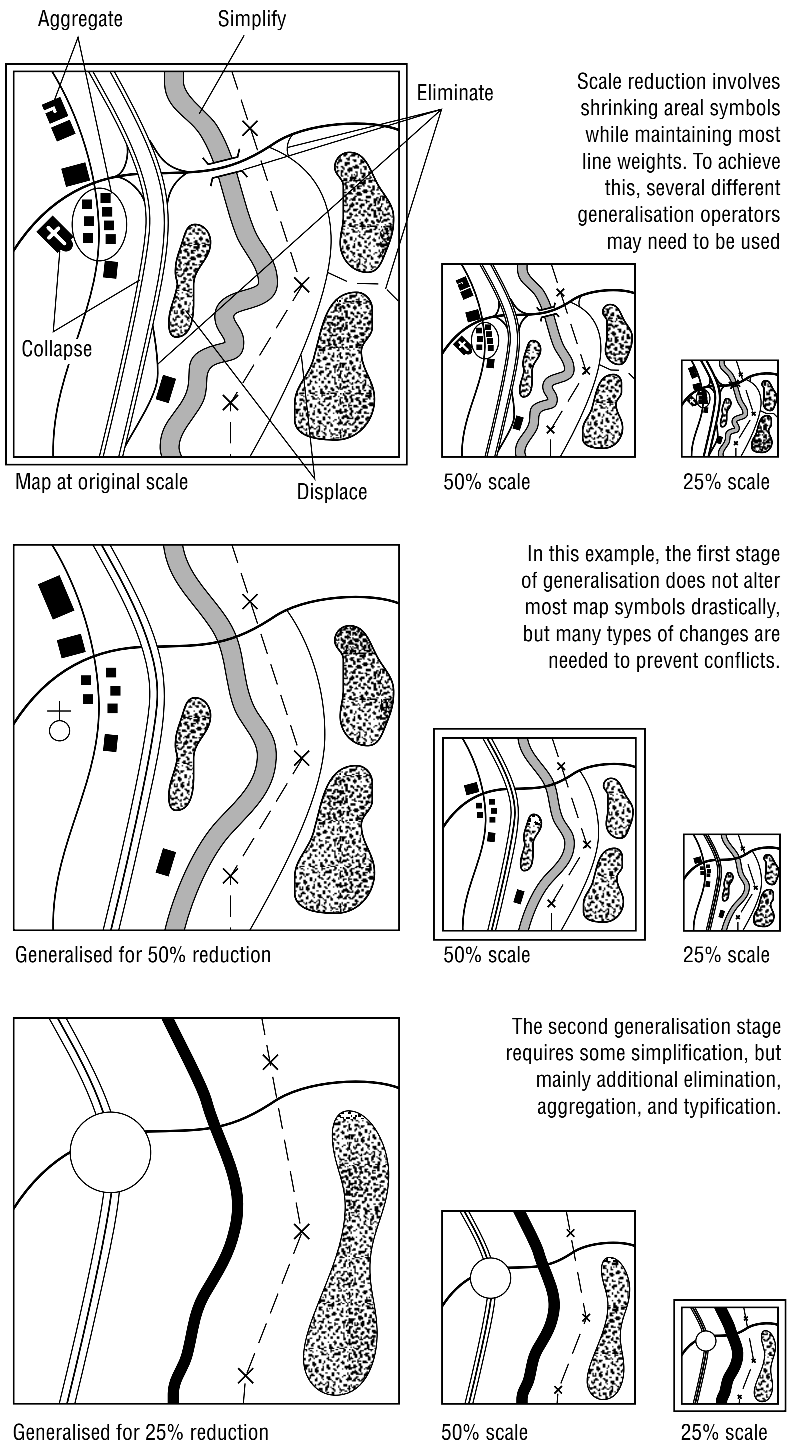


Fig 4. Application of map generalisation operators (cf. discussion in section 4.3, Table 1).

Table 1 Relations of generalisation operators and data (operands).

	TYPE OF SPATIAL DISTRIBUTION				
OPERATOR	Points	Lines	Areas	Fields	Hierarchies
Eliminate/ Select	*Weed based on attributes or priorities*	*Eliminate minor branches*	Eliminate small areas or sub-polygons	*Recode less significant values to null*	Ignore nodes with few children
Simplify	Weed to min. neighbour distance	Eliminate minor segments or inflections	Remove islands and concavities	*Collapse category definitions*	Shift to lower level of detail
Smooth	Make distribution more uniform	Reduce angularity	Soften concavities and crenulations	*Average or convolve variations*	Average at nodes of tessellation
Aggregate/ Amalgamate/Merge	*Combine similar neighbours*	Simplify intersections	Delete edges between similar features	Interpolate to larger cell size	Derive lower levels from higher ones
Collapse	Replace by area symbol or convex hull	Combine nearly parallel features	Shrink to point or medial axis	*Merge similar categories*	Redefine or reorganise hierarchy
Displace	Disperse from each other and larger objects	Increase separation of parallel lines	Move away from linear elements	(not normally attempted)	Move data to less occupied neighbours
Enhance/ Exaggerate	Impute, randomise, or densify distributions	Impute or emphasise changes in direction	Complicate boundaries, impute inclusions	*Emphasise differences, equalise histogram*	Extrapolate to levels of higher resolution

Note: Table entries are suggestive only and are not intended to be exhaustive.
Underlined entries may require/result in topological transformations.
Italic entries require reference to attributes or change their domain.

line) and smoothing (by modifying coordinates on a line to plane away small irregularities), as cartographers normally do not make a conscious distinction between the two operations when simplifying the shape of a map object (Plazanet 1996; Ruas 1995b; Weibel 1997). One of the criteria that guided our choice of operators was that each operator should possibly be valid for all common data types including points, lines, areas, fields (usually raster data), and hierarchies (trees and recursive tessellations). This contrasts with Shea and McMaster's (1989) typology, where some operators are only applicable to certain data types. In Table 1, basic examples are given for each operator, and note is made of whether the operator may alter topological relations or affects the attribute domain. For some of the operators alternative terms found in the literature are also given.

Table 1 focuses on the 'how to' aspect of generalisation, categorising some functions that might exist in a process library (Brassel and Weibel 1988). Yet selection of such operators is also shaped by the objectives or 'whys' of generalisation. To achieve these objectives, each situation should be evaluated cartometrically to determine if communication goals are being met (Brassel and Weibel 1988; McMaster and Shea 1992). Table 2 describes this process in terms of simple rules that may be applicable depending on the generalisation objective(s). Terminology for 'cartometric criteria' is taken from a larger set described by McMaster and Shea (1992: 42–51), and can be described as:

1 *Crowding*: excessive feature density attributable to scale reduction;
2 *Conflict*: symbolism for features which overlap or cannot be distinguished;
3 *Consistency*: uniformity of symbolism and value classification across a map;
4 *Perceptibility*: maintaining legibility when features or symbols are shrunk.

Lastly, generalisation operators can be related to the fundamental data domains introduced in section 3.3, by discriminating between those that: (1) select or modify spatial primitives; (2) select or modify features; (3) transform the attribute domain; or (4) transform the spatial domain. This is useful because it helps to

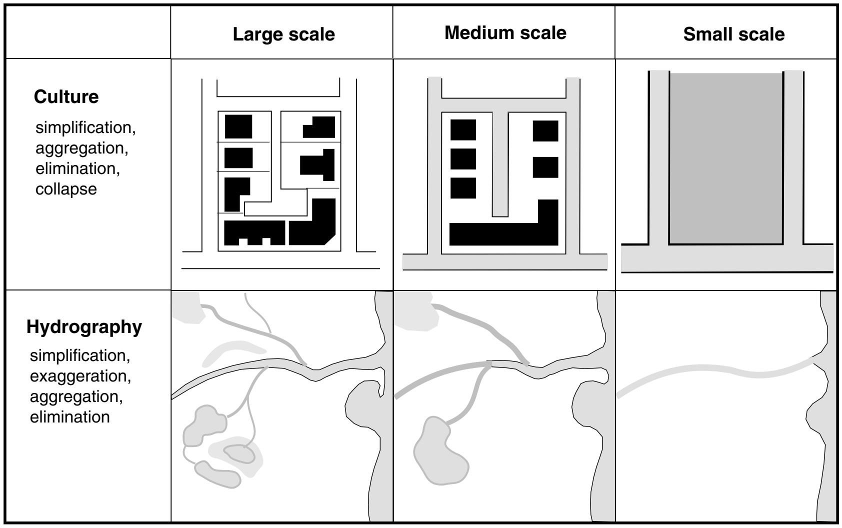


Fig 5. The set of appropriate generalisation operators varies depending on the feature classes and scales.

identify the point at which operators get applied, and identifies what types of side-effect they may have.

Knowing which data domains are targeted by a given procedure helps users (and applications) to select procedures from a process library (algorithms available to implement operators). The content and structure of the database must be appropriate for a given operator to work, and the manner in which an operator functions is highly dependent on what hooks data models and data structures provide for handling cartographic primitives, features, attributes, and space itself, as well as what types of constraint generalisation must satisfy (cf. sections 5.2 and 5.4). Clearly, it may be necessary to take several of these actions together, even if one approach is primary. In practice, operations from more than one domain will be invoked to generalise a given digital map for a stated purpose. Operations in different domains have many close relationships, and can be combined in a number of natural and effective ways. As a simple example, aggregation of class values in the attribute domain of a categorical land-use map to form superclasses – e.g. aggregating 'deciduous forest' and 'coniferous forest' to 'forest', or 'residential area' and 'industrial area' to 'built-up area' – will have an effect on the geometry of the primitive domain (some polygon boundaries will disappear) and on the feature domain (new and larger regions will be formed).

5 ELEMENTS OF A GENERALISATION SYSTEM

Whether generalisation functionality is implemented as an ad hoc set of tools made available in a toolbox, or represents a sub-system of a larger GIS or cartography system, or forms a stand-alone generalisation system is not in itself important. (See Openshaw and Alvanides, Chapter 18, for a similar view with regard to the implementation of spatial analytic functions.) What matters is that the necessary elements required to solve a given class or several classes of generalisation problems are made available in a way which enables the system or user to invoke the right actions. This section attempts to identify the elements that need to be present in an idealised (not yet available) comprehensive generalisation system. Discussion of these elements will serve as a review of selected existing techniques and will highlight critical issues requiring additional research. The systems-oriented approach helps to identify the interrelations between the various elements.

5.1 An idealised generalisation system

The following discussion is based on two constraining assumptions. First, the discussion here will be restricted to functions for generalisation in the narrow sense. That is, we assume that basic graphics functions needed for map production

Table 2 Rules for achieving map design objectives.

	CARTOMETRIC CRITERIA			
GENERALISATION OBJECTIVES	Crowding	Conflict	Consistency	Perceptibility
Reduce/Maintain Graphic Complexity	Enforce radical law where practical	Displace or eliminate overlapping symbols	Apply tolerances and thresholds uniformly	Weed detail to perceptual limit
Maintain/Standardise Spatial Accuracy	Respect map accuracy standards	Displace less accurate or critical features	Generalise uniformly within a given feature class	Do not represent features that cannot be distinguished
Maintain/Standardise Attribute Accuracy	Streamline attribute classification	Do not construct overlapping symbol classes	Always use the same symbol for a given attribute within a map	Limit no. of value classes more as features shrink
Maintain/Standardise Aesthetic Quality	Use minimum appropriate symbol sizes	Maintain figure/ground rels., use compatible colours, textures	Use distinct but related colours and line styles	Be judicious when using multi-variate symbolism
Reduce/Maintain Attribute Hierarchy	Combine related feature classes	Eliminate minor features by size or attribute	Use same value classification everywhere for a feature class	Ensure that the classification conveys enough information

Note: Table entries are suggestive only and are not intended to be exhaustive.

(cartographic symbolisation, projections, zooming, etc.) will be available to the envisaged ideal system, or will be supplied by a carrier system (e.g. a GIS). Second, we assume that a human (user) will be involved in the generalisation process in some capacity, interacting with the system. User involvement may range from close to zero (invoking 'batch' modules) to a constant stream of interactions (fully interactive mode of operation, with no built-in machine 'intelligence'). In all cases, users will always be involved, even if the involvement is restricted to visual evaluation of results. That is, the more the system relies on user interaction, the more responsibility is put on the user. Cartographic experts will obtain better results than novices.

The next question we have to ask is what software paradigm is used to build the system. A look at prior research in digital cartographic generalisation reveals that neither purely algorithmic methods (Leberl 1986; Lichtner 1979) nor knowledge-based techniques such as expert systems (Fisher and Mackaness 1987; Nickerson 1988) have been capable of solving the problem comprehensively. While the former suffer from a lack of flexibility (since they are usually designed to perform a certain task) and from weak definition of objectives, the development of the latter was impeded by the scarcity of formalised cartographic knowledge and the problems encountered in acquiring it (Weibel et al 1995). More recent research has therefore concentrated on systems that attempt to integrate different paradigms into a single coherent approach. Workbench systems designed to support research on more complex, contextual generalisation operators such as aggregation and displacement today use a combination of algorithmic (deterministic) and knowledge-based techniques commonly implemented on the basis of object-oriented technology. Examples of this class of research systems are MAGE (Bundy et al 1995; Jones et al 1995) and Stratège (Ruas 1995a; Ruas and Plazanet 1997). Another paradigm from artificial intelligence research is that of autonomous agents, which is just starting to be applied to generalisation (Baeijs et al 1996). If we consider how a system could be used in a production environment to solve actual generalisation problems, we find that the decision support system (DSS) paradigm, a strategy often used to solve ill-defined problems, may be an appropriate approach to take. A particular approach in this vein has been termed *amplified intelligence* (Weibel 1991). As visualisation and generalisation are essentially regarded as creative design processes, the human is kept in the loop: key decisions default explicitly to the user, who initiates and controls a range of algorithms that automatically carry out generalisation tasks (Figure 6). Algorithms are embedded in an interactive environment and are

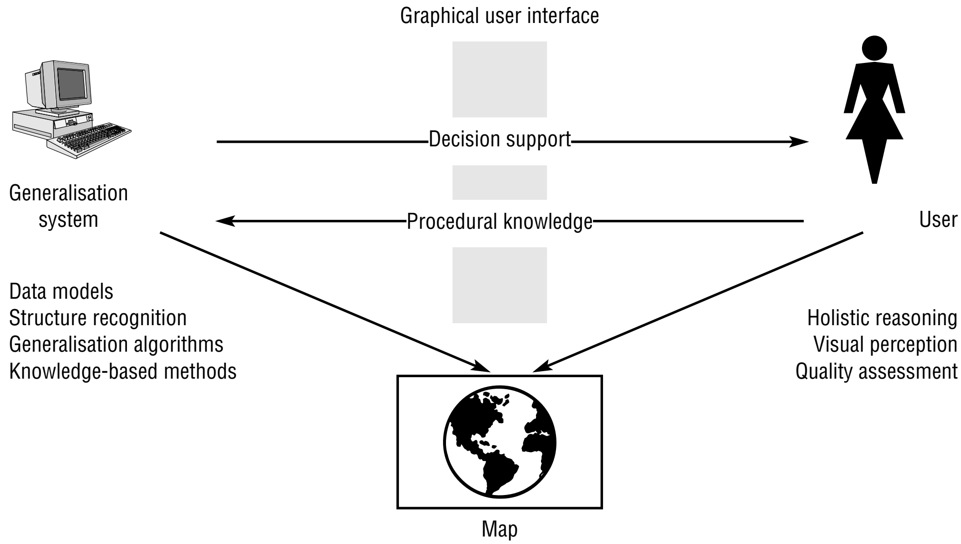


Fig 6. The concept of amplified intelligence for map generalisation.

complemented by various tools for structure and shape recognition giving cartometric information on object properties and clustering, spatial conflicts and overlaps, and providing decision support to the user as well as to knowledge-based components. Ideally, interactive control by the user reduces to zero for tasks which have been adequately formalised and for which automated solutions could be developed.

In a system such as Figure 6 depicts, algorithms serve the purpose of implementing tasks for which sufficiently accurate objectives can be defined. This includes cartographic generalisation operators such as simplification, aggregation, or displacement; functions for structure and shape recognition, including shape measures, density measures, and detection of spatial conflicts; and model generalisation functions.

Knowledge-based methods can be used to extend the range of applicability of algorithms and code expert knowledge into the system. This initially builds on methods for knowledge acquisition; for instance, machine learning may help to establish a set of parameter values that controls the selection and operation of particular algorithms in a given generalisation situation (Weibel et al 1995). Second, procedural knowledge and control strategies are needed: once the expert knowledge is formalised, it can be used to select an appropriate set and sequence of operators and algorithms and to establish a strategy to solve a particular generalisation problem.

An ideal system builds on a hierarchy of control levels. The human expert makes high-level design decisions and evaluates system output. Knowledge-based methods operate at an intermediate level and are responsible for selecting appropriate operators and algorithms and for conflict-resolution strategies. Finally, algorithms are the workhorses at the lowest level, forming the foundation of everything else.

In summary, the following main areas – which will be discussed in the remainder of this section – need to be addressed to implement a comprehensive generalisation system based on the above assumptions:

- data representations and data models;
- structure and shape recognition;
- generalisation algorithms, including model generalisation;
- knowledge-based methods;
- human–computer interaction;
- generalisation quality assessment.

5.2 Data representations and data models

Most generalisation algorithms available today are related to operators such as selection, simplification, or smoothing which are context-independent, treating map objects largely independently of their context. Few solutions are available for context-dependent operators such as aggregation or displacement which the spatial context (spatial relations of objects, object density, etc.) triggers and guides to completion. Various authors have argued that the scarcity of available context-dependent generalisation algorithms is caused by the fact that commonly used spatial data models are unable to provide adequate support of such complex functions, in particular those requiring a representation of proximity relations between disjoint objects (Bundy et al 1995; Dutton 1984; Ruas and Lagrange 1995; Weibel 1997). In recent years, research has therefore started to exploit alternative data models. The problem needs to be addressed at two levels, involving representations for geometric primitives as well as complex data models.

5.2.1 Representations for geometric primitives

Adequate data structures must be available for representing geometric primitives (points, lines, areas), including methods such as polygonal chains (or polylines), mathematical curves, and rasters. These primitive representations must be capable of capturing the shape of the modelled features accurately and in a compact and expressive way.

In vector mode generalisation, polylines are by far the most commonly used representation scheme for geometric primitives. Regardless of its popularity, the polyline representation also imposes impediments on the development of generalisation algorithms (Fritsch and Lagrange 1995; Werschlein 1996), essentially restricting the design options to simplification (vertex weeding) and smoothing (vertex modification). The fact that a polyline is simply a sequence of points implies that it is difficult to model entire shapes such as a bend of a road properly or compactly. Complementary representations to polylines are therefore being investigated. Work by Affholder (reported by Plazanet et al 1995) on geometric modelling of road data is an example of fitting the representation scheme more closely to the object that needs to be represented. Affholder models roads by a series of cubic arcs, leading to a more compact and also more realistic representation of these manmade features which offers potential for the development of new algorithms.

Parametric curves based on curvature can be usefully exploited for shape analysis as critical points such as inflection points show up as extremes (Werschlein 1996). The magnitude of these extremes exhibits the size of the shape that is associated with the critical point and thus allows prioritisation.

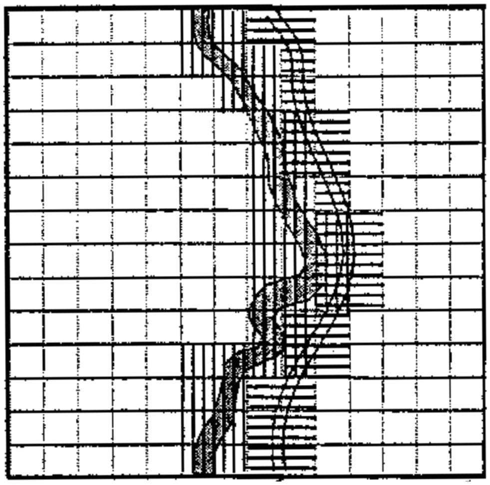
Wavelets (Chui 1992) are a relatively untried but promising approach to generalisation of both surfaces (Schröder and Sweldens 1995) and lines (Fritsch and Lagrange 1995; Plazanet et al 1995; Werschlein 1996). They either require a raster representation or, for vector data, that its geometry be first transformed into a function (e.g. a parametric curve). A geometric basis function, the 'mother wavelet', is then applied to fit the representation over doublings of resolution. Wavelet coefficients can be analysed to determine critical points and shapes, and they can also be filtered to yield generalised versions of the original feature. It is also possible to eliminate entire shapes selectively by setting the coefficients of the wavelets supporting a particular shape to zero (Werschlein 1996).

5.2.2 Complex data models

Complex data models let one integrate primitives into a common model (e.g. a topological vector data model) and record their spatial and semantic relations. While the search for alternative primitive representations is mainly guided by the requirements of representing and analysing shapes, research into complex data models is driven by the need to support context-dependent generalisation. Improved complex data models must: allow representation of relevant metric (proximity), topological, and semantic object relations within and across feature classes; enable object modelling (including differentiation between primitives and features, complex objects, and shared primitives); and permit the integration of auxiliary data structures such as triangulations, uniform grids, or hierarchical tessellations for computing and representing proximity relations.

As a consequence of these requirements the main data model should be an object-oriented extension of the basic topological vector model (as opposed to layer-based). Data models of this kind are now beginning to appear in some commercial GIS. Integrated auxiliary data structures for proximity relations are not yet available in commercial systems, but research is under way in that direction.

Data structures for proximity relations are commonly based on tessellations (see Boots, Chapter 36 for a comprehensive review of tessellations in GIS). Space-primary tessellations use regular subdivision of space and can be used as a simple mechanism to assess spatial conflict within


(a)

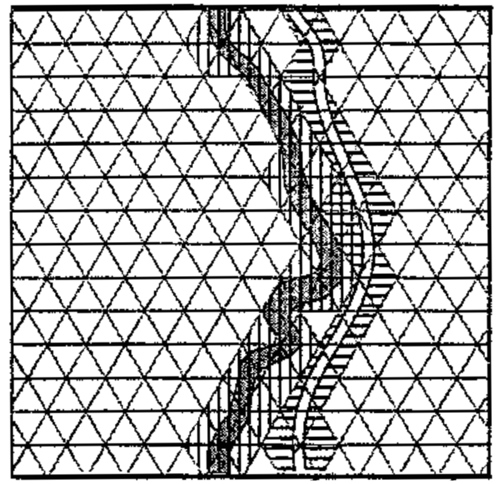

(b)

Fig 7. Space-primary assessment of spatial conflict between a river and a road using alternative tessellations: (a) rasterising to a rectangular grid; (b) rasterising to a triangular grid.

a fixed resolution, usually relating to the resolution of the target map (Figure 7). They can also be turned easily into hierarchical data structures. By discretising space in a hierarchical fashion, vertices and entire primitives can be coalesced or eliminated when several are found to occupy the same location (a 'chunk' of space). Encoded features can have addresses that indicate where and how big they are, allowing access both by location and resolution. Generalisation often proceeds in such methods by aliasing the positions of points or grid cells to some median location (see Figure 8). Alternatively, detected overlaps or coalescing primitives can be resolved by displacement. Quadtrees (Samet 1990) and pyramids are commonly used to partition map space hierarchically; conventional approaches index planar coordinates using rectangular subdivision. Their use in geoinformation processing, however, has been principally limited to multi-resolution image reconstruction. Spherical quadtrees (Dutton 1989; Fekete 1990; Goodchild and Yang 1992) enable planetary indexing of global geographical coordinates by partitioning the facets of regular polyhedra into forests of triangular quadtrees. A line generalisation method via hierarchical coarsening using a triangular quadtree structure – the quaternary triangular mesh (QTM) – has been presented by Dutton and Buttenfield (1993) and Dutton (1997). This is illustrated in Figure 8 in which the 'level' of generalisation denotes the resolution (doubling of scale) of each hierarchical encoding: level 16 corresponds to 150 m, level 12 to 2.5 km resolution.

Most approaches to represent proximity relations between spatial objects accurately, however, have concentrated on the use of object-primary tessellations including Delaunay triangulations or Voronoi diagrams (Jones et al 1995; Ruas 1995a; Ruas and Plazanet 1997; Ware et al 1995; Ware and Jones 1996; Yang and Gold 1997). The data models used by Ruas (1995a) and by Bundy et al (1995) are both based on Delaunay triangulations. Both approaches concentrate on the support of methods for detecting and resolving spatial conflicts (e.g. feature overlap or coalescence), and both use the space subdivision scheme as a means to compute proximity relations, compute displacement vectors (if needed), and keep track of displacements. Beyond these similarities, however, the two data models take a different approach.

Ruas (1995a; see also Ruas and Plazanet 1997) subdivides map space according to the hierarchy of the road network. Within each of these irregular tiles, conflict detection and resolution again takes place, starting at level 1 and proceeding to finer levels. A local, temporary Delaunay triangulation is

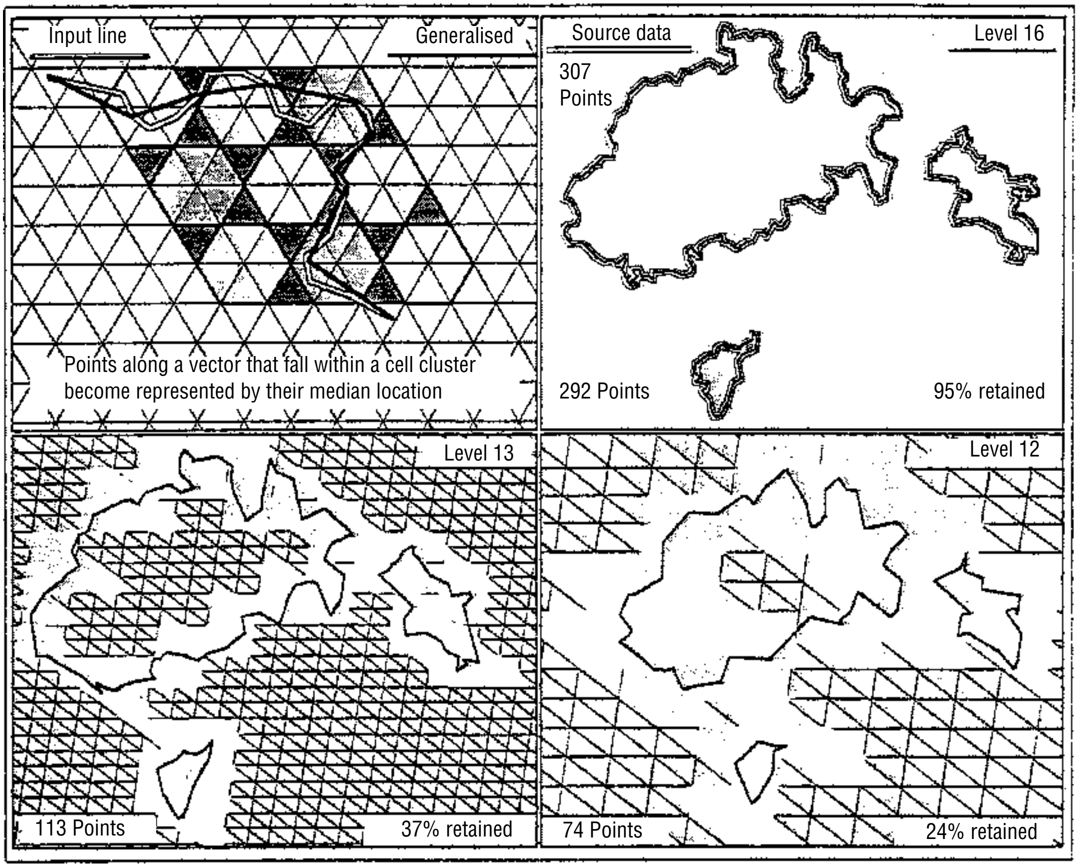


Fig 8. Line simplification via hierarchical coarsening using a quaternary triangular mesh (QTM).

Fig 9. Local Delaunay triangulation between buildings and adjacent roads (after Ruas 1995a).

then built within each partition to negotiate spatial conflicts there. The triangulation connects the centroids of the small area objects and point objects falling within the tile, as well as projection points on the surrounding roads forming the tile boundary. The edges of the triangulation are classified according to the types of object they connect. Thus in Figure 9, edge e1 denotes an edge connecting two buildings; e2 connects two vertices on a road; and e3 connects a building and a road. If the shape of a bounding road is changed or buildings are enlarged or moved, the triangulation is used to determine any conflicts that might have arisen. Displacement vectors are then computed from the distances between objects and displacement propagation is activated using distance decay functions. This is illustrated in Figure 10, in which a road (a) is modified, leading to overlap (b). Displacement vectors are calculated (c) and buildings are rotated

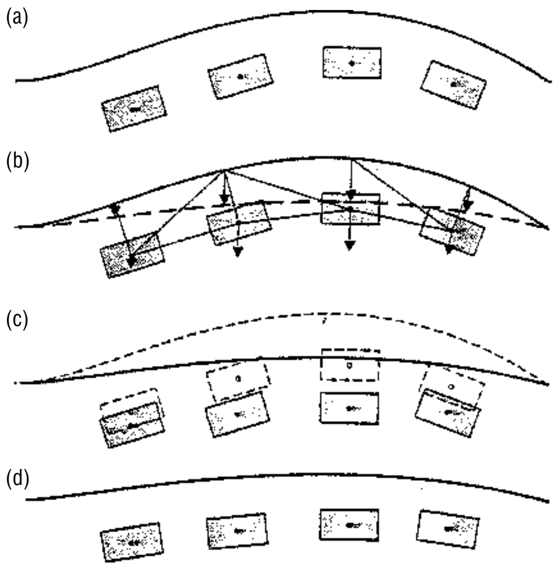


Fig 10. Displacement of buildings after simplification of a road (after Ruas 1995a).

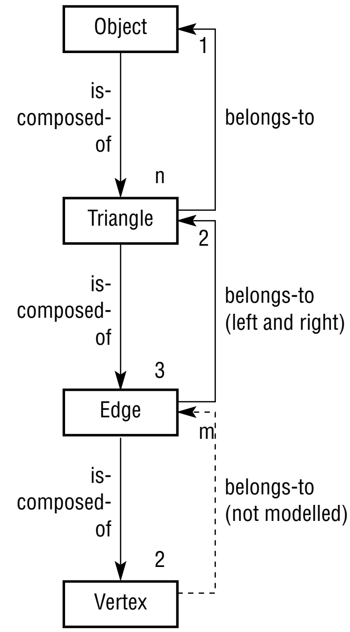


Fig 12. Entity relationships in the simplicial data structure (after Jones et al 1995).

and realigned with the modified road (d). (For the sake of clarity only the road centreline is shown in this figure; the symbol width of the road would be taken into account when computing the displacement vectors.)

In the triangulated data model developed by researchers at the University of Glamorgan (Bundy et al 1995; see also Jones et al 1995; Ware et al 1995; Ware and Jones 1997) the triangulation forms the core of the data model. Rather than connecting centroids of map objects, a constrained Delaunay triangulation of all the vertices of all map objects is built (Figure 11). The resulting simplicial data structure (SDS) is represented through a set of relations which are stored by pointers corresponding to the entity relationships illustrated in Figure 12. Since the SDS comprises all the geometric information of the original objects, all generalisation operations are carried out directly on the SDS. The target application for the MAGE system built around the SDS is the generalisation of large-scale topographic map data of the Ordnance Survey of Great Britain. To that end, a palette of generalisation operators has been developed including object exaggeration (enlargement), object collapse (constructing the centreline of road casings), operators for areal object amalgamation, and building simplification using corner flipping of triangles.

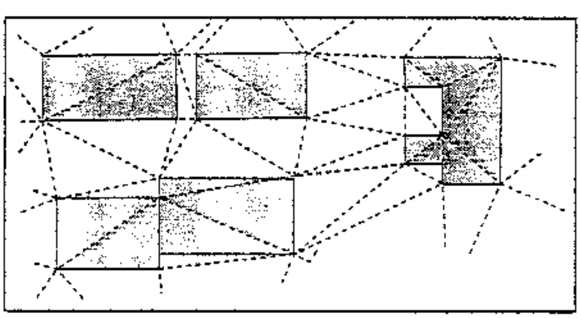


Fig 11. A sample section of the constrained Delaunay triangulation forming the simplicial data structure (after Ware et al 1995).

5.3 Structure and shape recognition

As discussed in section 4.1, structure and shape recognition (cartometric evaluation) are logically prior to the application of generalisation operators (Brassel and Weibel 1988; McMaster and Shea 1992). They can determine when and where to generalise and inform the selection, sequencing, and parameterisation of a set of generalisation operators for a given problem. Because cartographic data tend not to be richly structured, parts of features (e.g. a hairpin bend on a road or an annex of a building) are rarely coded explicitly. Likewise, little information is normally stored on shape properties of map features. Structure and shape recognition therefore aims at enriching the semantics of source map data, and deriving secondary metric, topologic, and semantic properties including shape characteristics, object density and distribution, object partitioning, proximity relations, relative importance (priority) of map objects, and logical relations between objects.

In recent years, research in this area has intensified. First attempts at cartographic line characterisation were made by Buttenfield (1985). Recently, an approach has been presented by Plazanet (Plazanet 1995, 1996; Plazanet et al 1995) which generates a hierarchical segmentation of cartographic lines according to a *homogeneity* criterion. The resulting tree structure is called the 'descriptive tree'. Figure 13 illustrates such a tree; the homogeneity of the individual sections is intuitively apparent. The homogeneity definition used to split up the line is based on the variation of the distances between consecutive inflection points which have been previously extracted (Figure 14). While the objective of segmentation is mainly to obtain sections of the line that are geometrically sufficiently homogeneous to be tractable by the same generalisation algorithm and parameter values, further information is added to the descriptive tree that characterises the *sinuosity* (and thus the prevailing geometric character) of each line section. A variety of measures can be obtained from the deviation of the cartographic line from a trend line formed by the base line connecting consecutive inflection points. These measures are then used to classify line sections according to their degree of sinuosity.

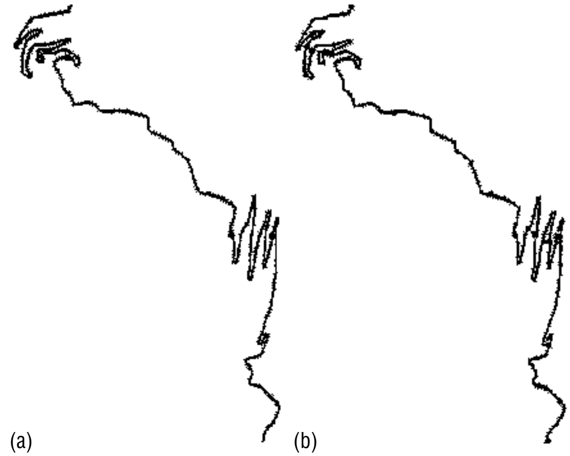


Fig 14. (a) Detected inflection points; (b) critical points retained automatically for segmentation.
Source: C Plazanet, IGN France.

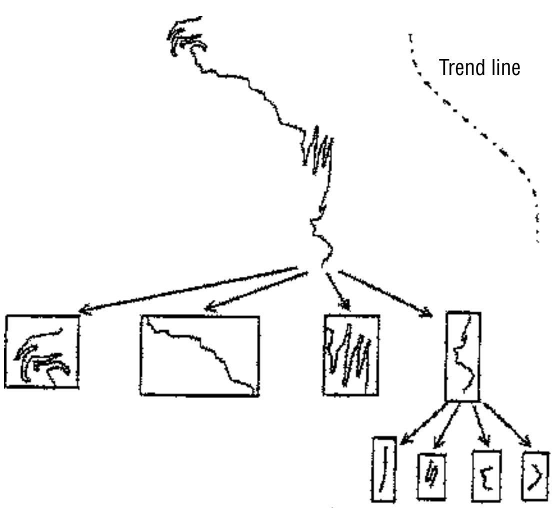


Fig 13. An example of line segmentation into a descriptive tree.
Source: C Plazanet, IGN France.

Analysis of complex situations involving disjoint objects such as buildings and roads in built-up areas can obviously benefit from data models such as those discussed in section 5.2.2. Proximity and adjacency relations can be assessed and possible overlaps detected by direct analysis of the data model. More complex relations involving many objects, however, require further processing. An example of such a procedure has been presented by Regnauld (1997), who proposed the use of the minimum spanning tree (MST) to detect clusters of buildings of like shape and alignment in order to form candidate sets for aggregation and typification operations.

In the area of terrain generalisation, Weibel (1992) has reported on the use of procedures for geomorphometric analysis to drive the selection of appropriate generalisation methods. Geomorphometric analysis is first applied at the global level, segmenting an entire DTM into homogeneous regions amenable for a particular generalisation method in an approach similar in nature to Plazanet's (1995) technique for line segmentation. Next, structure lines (drainage channels and ridges) are automatically extracted from the DTM to form the so-called 'structure line model' (SLM) which is seen as a 3-dimensional skeletal representation of the terrain surface and used as a basis for the generalisation method termed 'heuristic generalisation'. This procedure generalises the SLM by modifying links in the networks of channels and ridges and interpolates a generalised DTM from the modified SLM (Figure 16 (b) shows a result of this procedure).

5.4 Generalisation algorithms

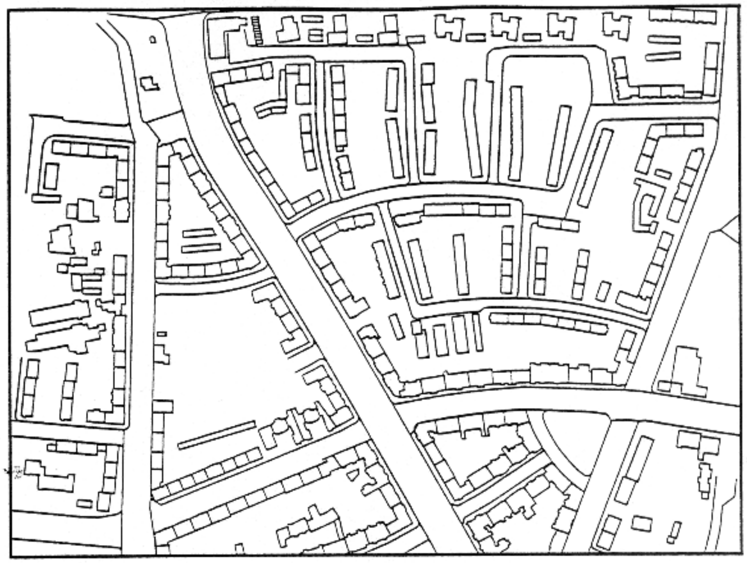
In section 4.2, it was noted that generalisation algorithms implement generalisation operators which in turn define the spatial transformations necessary to achieve generalisation. Generalisation algorithms are thus at the heart of the generalisation system, 'making it happen'. As Figure 5 illustrates, however, generalisation algorithms tend to be phenomenon-specific because they must take into account the particular shape properties and semantics of the real-world features they aim to depict in a generalised version. Only careful analysis of the structure and shape of map objects – exploiting the resources of a rich spatial data model – can give generalisation algorithms the guidance they need.

Countless generalisation algorithms have been developed over the past three decades; this discussion is restricted to algorithms for vector data. Raster-based algorithms are reviewed by Schylberg (1993); they are less common, but naturally lend themselves to implementation of context-dependent operators, as Figure 7 indicates. Most vector algorithms are intended to generalise point and line primitives using context-independent operators such as selection, simplification, and smoothing (see McMaster and Shea 1992 for descriptions). Research in more recent years has been characterised by increasing interest in more complex context-dependent operators such as aggregation and displacement. Displacement algorithms have profited from data models such as the ones discussed in section 5.2, but also from research in displacement propagation functions (Mackaness 1994). Examples of aggregation algorithms include procedures for area patch generalisation described by Müller and Wang (1992) as well as the research at the University of Glamorgan by Jones et al (1995).

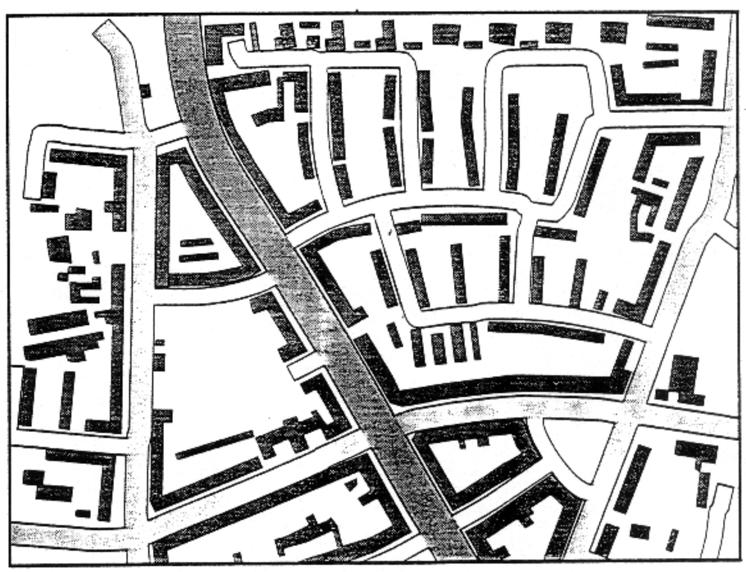
Attention in research on generalisation algorithms has also turned to the development of algorithms which are constrained by the particular requirements and characteristics of specific feature classes. Instead of generalising line or polygon primitives, the focus is on the feature classes that these primitives purport to represent. That is, specific methods for generalising building outlines, traffic networks, or polygonal land-use maps are developed. Such techniques may be based on more primitive algorithms, integrating them to build fine-tuned methods. An example of a system that has employed specialised algorithms at an early stage to develop functionality for large-scale topographic map generalisation is the CHANGE system which integrates two decades of research at the University of Hanover (Grünreich et al 1992). This system includes specific algorithms for generalisation of roads (centreline generation, simplification, symbolisation), building generalisation (outline simplification, aggregation), and identification and editing of spatial conflicts. A sample output is shown in Figure 15. It represents the result of a fully automated procedure; interactive editing is usually necessary to clean up residual problems.

Other research has addressed the generalisation of road networks (Mackaness and Beard 1993; Thompson and Richardson 1995). Owing to the topologic constraints of networks, these methods are based on an analysis of the network structure using graph-theoretic algorithms. Techniques for terrain generalisation have been proposed by Weibel (1992), who also summarises other approaches. A strategy is used that employs three types of generalisation methods, two of which apply filtering techniques, while the third is based on an extraction of the networks of drainage channels and ridges (cf. section 5.3; see also Hutchinson and Gallant, Chapter 9). Figure 16 is based on an application of the third method and shows: (a) an original surface (7.75 × 5.5 km; 25 m resolution); (b) a generalised surface, resulting from the extraction and generalisation of the network of topographic structure lines (channels and ridges); and (c) a further modification of the automatically generalised surface through interactive retouching to enhance prominent landforms using a DTM editor developed by Bär (1995). This editor offers a range of tools, most of which are implemented as local convolution filters in the spatial domain and which can be controlled interactively.

Developing algorithms which can meet the needs of particular feature classes, scale ranges, and map



Result of automated generalisation using CHANGE



Scale 1:5000

Scale 1:10 000

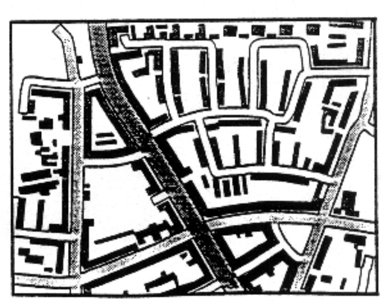


Fig 15. An example of large-scale topographic map generalisation using the CHANGE system.
Source: Grünreich et al 1992: courtesy of the Institute of Cartography, University of Hanover. Note that scale is only **approximate.**

types requires that the constraints which govern a particular generalisation task are defined accurately (Beard 1991; Weibel 1997). A good example of a constraint-based algorithm is the procedure proposed by Berg et al (1995) for the simplification of polygonal maps. Their algorithm satisfies four constraints:

1 all points on the simplified polygon boundary (chain) are within a prespecified error distance from the input boundary;
2 the simplified chain has no self-intersections;
3 the simplified chain may not intersect other chains of the polygonal map;
4 all points of an additional point set lie to the same side of the resulting polygon boundaries as before simplification.

Finally, the algorithms toolbox must also include methods for model generalisation. Relatively little attention has so far been paid to this segment of generalisation, however. The volume edited by Molenaar (1996a) contains a selection of papers on the topic. Weibel (1995b) discusses the requirements of model generalisation and their differences from those of cartographic generalisation. Heller (1990) presents a method for filtering a grid or TIN DTM which can be used for model generalisation of terrain models (see also section 3.4).

5.5 Knowledge-based methods

If a generalisation system were based solely on the data models and algorithms discussed above, much of the higher-level reasoning and decision strategies would be lacking, making it necessary to rely entirely on the user for the provision of this missing knowledge. Knowledge-based methods have been proposed as a way to overcome this reliance on the individual user and to build more completely automated solutions. Knowledge-based methods with a potential applicability to generalisation encompass expert systems (or knowledge-based systems) as well as machine-learning techniques including methods such as inductive learning, case-based reasoning, genetic algorithms, or artificial neural networks (Carbonell 1990). The potential of these methods lies in two areas: in acquiring and representing human knowledge *explicitly* (e.g. inductive learning for knowledge acquisition and rules of an expert system for knowledge representation), and in complementing or replacing algorithmic techniques by use of *implicitly* encoded knowledge (e.g. knowledge which is latently contained in large sets of examples) as well as computational learning strategies (e.g. genetic algorithms or neural networks: see Fischer, Chapter 19).

Use of knowledge-based methods for the latter purpose has been restricted to a few isolated attempts to use genetic algorithms, neural networks, or case-based reasoning in generalisation, and is still in an undeveloped state (see Weibel et al 1995 for a review). The former area, however, has received more attention. Whatever the intended use of knowledge-based methods may be, knowledge acquisition (KA) is the key to success. This is particularly true for expert systems, as they derive their power from the knowledge they contain and not from the particular knowledge representation schemes and inference mechanisms they employ. Because of the scarcity of available formalised cartographic knowledge, success of expert generalisation systems to date has been limited (with a few exceptions, such as that described by Nickerson 1988), a situation which has sometimes been termed the ‘knowledge acquisition bottleneck’.

According to Armstrong (1991) cartographic knowledge takes three different forms. Geometrical knowledge describes the geometry (locations), shape, and distribution of cartographic objects. Structural knowledge represents the structure of cartographic features in terms of their geomorphological, economic, or cultural meaning, and thus relates to the term ‘semantic knowledge’ used by other authors (e.g. Chang and McMaster 1993). Finally, procedural knowledge is used to select the appropriate generalisation operators, algorithms, and parameter settings required to perform a generalisation task. It is the knowledge that is needed to control the flow of operations. While geometric knowledge is largely contributed by methods for structure and shape recognition (section 5.3), and structural knowledge can be feature-coded into the database (or possibly extracted by shape analysis), the acquisition of procedural knowledge is largely an open problem. Its main task is to find rules which relate generalisation operators, algorithms, and parameter values to map scale, map purpose, feature classes, and shape properties. That is, procedures are to be linked to structure and semantics.

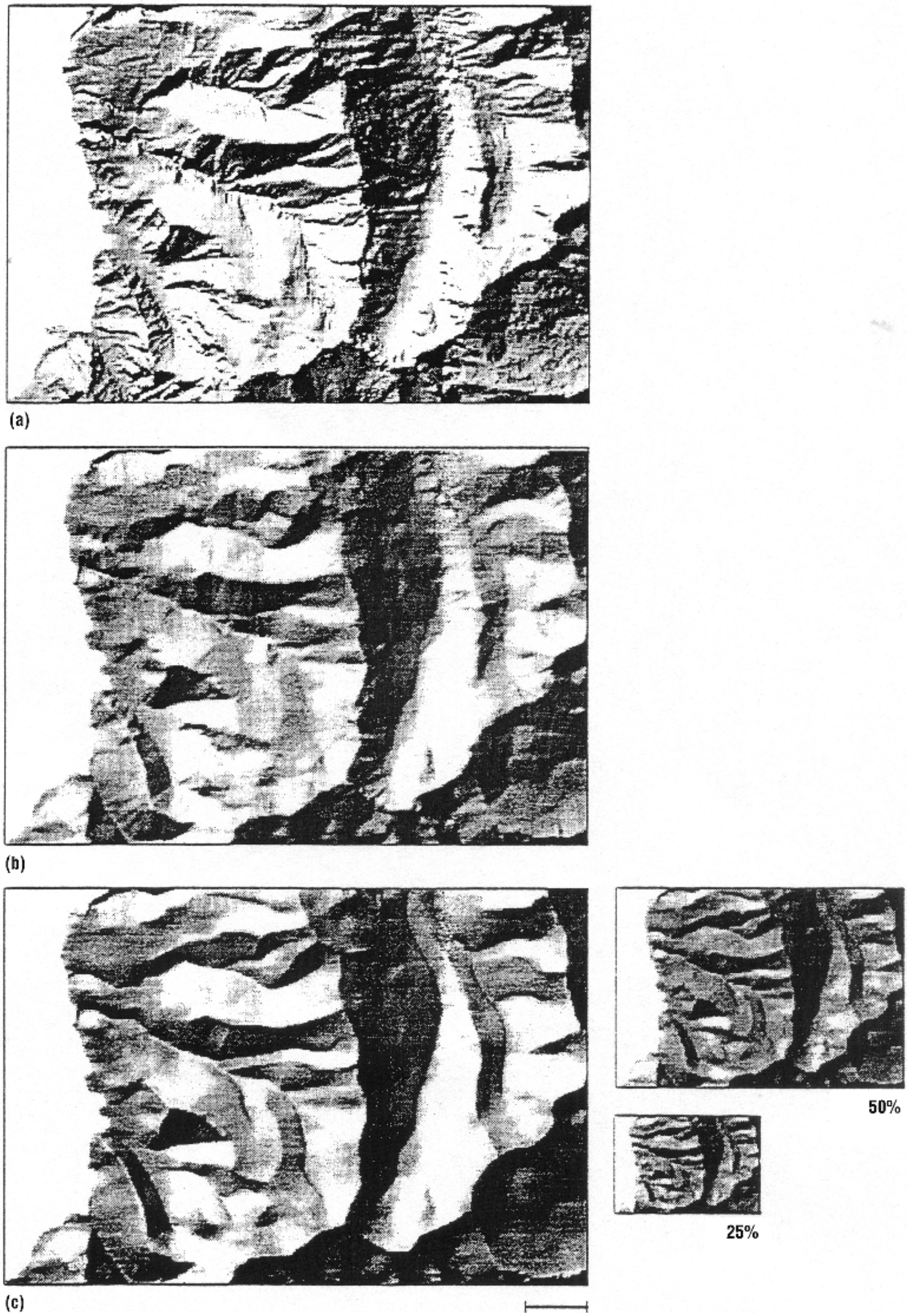


Fig 16. Terrain generalisation.
Source: DTM data courtesy of Swiss Federal Office of Topography.

Cartographic knowledge is different from other knowledge types (e.g. the knowledge needed in medical diagnosis) in that it is essentially graphical and therefore hard to verbalise and formalise. It may be acquired from different sources, necessitating different KA methods, which can be exploited in combination. Weibel (1995b) and Weibel et al (1995) discuss the potential of various KA methods and knowledge sources. The obvious source of knowledge is the *human expert* (cartographer). According to McGraw and Harbison-Briggs (1989), methods for eliciting knowledge from experts include interviews, learning by being told, and learning by observation. In generalisation, direct knowledge elicitation from experts has been restricted to projects linked to national mapping agencies (NMAs), such as those described by Nickerson (1991) or Plazanet (1996). *Text documents* form a second possible knowledge source. Apart from textbooks, written guidelines are available at NMAs, for example coding guides for digitising hardcopy maps (USGS 1994). These textual descriptions, often including positive and negative sample illustrations, may be used as a basis to develop formal rules. In summarising an attempt to cast generalisation guidelines in use at Ordnance Survey of Great Britain into rules, Robinson (1995) observes that the resulting rules revealed that the written guidelines were incomplete and often vaguely specified. *Maps* as a third knowledge source embody cartographic knowledge in graphical form. It may be hoped that a study of the evolution of features across the scales of a map series can reveal the procedural knowledge that was used to create the generalisation. Practical experiments using this type of 'reverse engineering' procedure have been useful in establishing quantitative relations between scales such as the percentage of objects retained for specific feature classes (Leitner and Buttenfield 1995), but they have also demonstrated the difficulty of reliably identifying more complex procedural knowledge such as the operators used to produce a generalisation (Weibel 1995b). It is often impossible to determine the operations that led to the result from the result alone. Finally, *process tracing* in interactive systems offers a method that could complement KA from experts. Instead of eliciting knowledge directly from experts, interactions of the expert with an interactive system are logged and later analysed to extract rules. Thus, the system acts as a mediator which already achieves a first step of translating human knowledge into the 'language' of generalisation systems. Use of this approach has been proposed by several authors, including Weibel (1991) and McMaster and Mark (1991). An implementation of this method to determine appropriate parameter values for line generalisation algorithms is described by Weibel et al (1995) and Reichenbacher (1995). The trace of interactions is analysed using inductive machine-learning algorithms in order to extract rules. Further experiments using inductive learning have been carried out by Plazanet (1996).

5.6 Human–computer interaction

Assuming that any comprehensive generalisation system is likely to take at least a partially interactive approach, consideration must be given to the design of user interfaces for generalisation. Human–computer interaction (HCI) in GIS and cartographic systems has profited greatly from the widespread availability of graphical user interfaces (GUI), but the specific requirements of generalisation may necessitate the development of optimised HCI mechanisms. Specific HCI mechanisms are needed during several phases of the development and use of generalisation systems: during algorithm development and testing, for selection and fine-tuning of generalisation algorithms and control parameters, for the evaluation of results, for retouching, and more.

Beard and Mackaness (1991) discuss the problem of how the 'cognitive responsibility' of the design process is best shared between the generalisation system and the user, and how the general workflow could be captured in the user interface. According to the general user interface requirements for generalisation systems proposed by McMaster and Mark (1991), the user interface should provide a broad set of generalisation operators, tools for identifying map features, assistance in selecting parameters for algorithms, warnings about inconsistencies, and traces of generalisation actions. User feedback should include hypermedia-based documentation and diagrams, graphical and numeric measures of success, and highlighting of features or regions in need of generalisation. Chang and McMaster (1993) report on a prototype system that implements parts of these elements, and develops specific HCI mechanisms to support them. The system was mainly intended for experimentation with the different line generalisation algorithms described by McMaster (1987). Results of up to four algorithms can be displayed, and tolerance parameters of the algorithms can be controlled via a slider bar, effecting real-time generalisation. The slider bar interaction technique was developed concurrently in the MGE Map Generalizer system described by Lee (1995). Schlegel and Weibel (1995) developed a prototype system which was intended to illustrate some of the HCI requirements of a generalisation system useful for production. Elements that were added to the design included multiple windows – a working window and two windows to display the map at the source and target scale, respectively – together with extensive feature selection functions (e.g. by selection via a histogram of shape measures), and full symbolisation with correct symbol size at target scale (necessary to assess the need for displacement). Finally, a novel interaction technique termed *generalisation by example* was proposed by Keller (1995). To specify tolerance parameters for a line generalisation algorithm, the user draws a representative sample line. The system picks up this sample and finds the parameter value(s) which can best reproduce the example with the specified generalisation algorithm; the optimisation procedure uses a genetic algorithm.

5.7 Generalisation quality assessment

As is true for digital cartography in general, assessment of the quality of generalisation results has received relatively little attention in research so far. The availability of a comprehensive palette of evaluation methods and strategies, however, is indispensable for progress in generalisation research, making it possible to assist such diverse tasks as the comparative appraisal of algorithms or entire software systems, the development of built-in evaluation functions for genetic algorithms, or the selection of positive examples for the training of neural networks (Weibel 1995b).

To date, evaluation has largely relied on visual assessment of the results obtained from a particular procedure or system, for instance by comparing digital results with a manually produced solution. This approach, however, is neither rigorous nor always possible, as the manual reference map may not be available. More rigorous, intersubjective, and repeatable methods are needed in digital systems. Quantitative assessment techniques can largely draw from structure and shape recognition methods (cf. section 5.3), as *a priori* structure recognition is similar to *a posteriori* assessment of results. The former analyses the structure of the objects in a source database, while the latter analyses the difference between a source and a derived database.

In order to assess the geometric performance of line simplification algorithms, McMaster developed a variety of geometric measures to analyse shape distortion in terms of the difference between the original and the simplified line (McMaster 1987). While this method is valid for entire lines, Mustière (1995) has proposed a series of measures which analyse a cartographic line for possible conflicts which might arise due to symbol enlargement, suggesting, for instance, elimination or enlargement of a particular bend. Checks for topological consistency such as tests for self-intersection, intersections between neighbouring lines, or point containment violations caused by line simplification are relatively easy to develop (Berg et al 1995). In general, quantitative assessment methods are weak when multiple objects are involved or the quality of an entire map needs to be characterised. This area still requires additional research.

As generalisation involves subjective decisions and aesthetic considerations, one cannot evaluate its results completely quantitatively, nor can quality assessment simply consist of a series of atomic tests and measures. An integrated approach is needed to capture the more holistic elements of generalisation. A methodology to integrate quantitative measures with qualitative judgements by cartographic experts in a consistent way has been proposed by Ehrliholzer (1995, 1996). Using it, an assessment process starts by carefully defining the relevant criteria to be used in describing the quality of a particular generalisation application. These criteria may be measurable, such as the minimum size of small areas, or qualitative and holistic, such as 'maintenance of the overall character of the map'. Application of these criteria will yield a 'quality description' with interval/ratio values for quantitative measures and symbolic descriptions or keywords for qualitative criteria. The two sets of results may then be integrated by transforming both into scores or ranks on a rating scale.

5.8 Digital generalisation in practice

Most commercial GIS today offer some generalisation functionality. Usually, however, generalisation capabilities in GIS are restricted to a few functions (e.g. line simplification, polygon aggregation, or various filters for raster data) which must be applied through independent commands in a toolbox approach (Morehouse 1995) or integrated to build more complex functions (Schlegel and Weibel 1995). Ruas (1995b) reviews the use of a general-purpose GIS (ARC/INFO) for the production of a database at scale 1:1 000 000 from a database at 1:100 000 at IGN France. Brandenberger (1995) reports on an experiment of producing a 1:10 000 scale map from data captured at 1:1000 using another major commercial system (Intergraph MGE).

Special-purpose commercial generalisation systems exist. The CHANGE system (Grünreich et al 1992), mentioned in section 5.4, builds on a suite of batch modules controlled by parameter sets. Figure 16 shows a sample run, in which the (approximate scale) maps represent the results of a fully automated procedure; following this first step, interactive editing is usually necessary to clean up remaining problem cases. Intergraph's MGE Map Generalizer product offers a palette of operators and algorithms embedded in an interactive environment under full user control (Lee 1995). Both systems have recently been evaluated in a software test as part of the activities of the Working Group on Generalisation of the OEEPE (Baella et al 1994; Rousseau et al 1995; Weibel and Ehrliholzer 1995).

Commercial GIS and cartography systems can be and are indeed used for the production of generalised maps today, which certainly is an improvement over the situation a decade ago when this was largely impossible. However, the generalisation workflow in practice still involves a great deal of interactive guidance and retouching (and essentially results in multiple representations if generalisation output is committed to one GIS database), owing to limitations of available generalisation capabilities. While generalisation functionality of current systems still needs considerable extension with respect to all of the elements of generalisation discussed above, perhaps the most limiting factors to date are the ones that form the foundations of a successful generalisation system: data representations and data models, generalisation algorithms, and structure and shape recognition (Schlegel and Weibel 1995).

Despite these limitations, however, the present situation in the commercial sector gives rise to substantial hope for future improvement. Since the first release of Intergraph's MGE Map Generalizer product in 1992 (Lee 1995), a growing number of GIS vendors including, among others, ESRI and Laser-Scan have become aware of the relevance of generalisation capabilities and have begun to extend the range of tools for generalisation and to articulate intentions to perform more long-term research and development (ESRI 1996; Hardy 1996; Woodsford 1995).

6 CONCLUSIONS

Generalisation is a highly complex process for which no simple solutions exist. Yet, after a period of relative stagnation during the late 1970s and the 1980s, generalisation has again attracted significant interest in the GIS community and beyond. The topic is well represented at key GIS conferences and pursued by several international working groups. The International Cartographic Association (ICA), the European Organisation for Experimental Photogrammetric Research (OEEPE), and the International Society of Photogrammetry and Remote Sensing (ISPRS) have all formed commissions and working groups to coordinate international research efforts. Similar research initiatives are being pursued at the national level in most of the larger industrialised countries. Additionally, the commercial sector is investing more effort in research and development in generalisation (see also Salgé, Chapter 50; Smith and Rhind, Chapter 47).

This situation has been caused by a confluence of three factors. First, there is an *increasing demand* for generalisation functionality by many types of GIS users, ranging from major national mapping agencies to specialised application builders. Apart from the 'classical' requirements of map production, the importance of generalisation in digital cartography and GIS is accentuated by continuing rapid growth of the number and volume of spatial databases and by the need to produce data meeting specific requirements and share them among different user groups (see Rhind, Chapter 56). Second, as a consequence of the first factor these forces have turned generalisation from a problem considered as too hard to tackle into *emergent solutions and market opportunities*, as technology suppliers (academic research and GIS vendors) react to these new demands. The research community is finding a renewed interest in these issues, addressing them with new conceptual approaches and more modern software architectures. GIS vendors are responding with apparent commitments to extend and improve their systems' generalisation capabilities. Third, the *technological setting has matured*; more powerful enabling technologies have become available, reliable, and affordable. This last factor is of utmost importance as it has finally created a situation where the processing power, networking capabilities, software engineering technologies, and graphics and analytical functions are available to approach realistically the task of developing complex generalisation functionality (see Batty, Chapter 21; Coleman, Chapter 22). The next few years will show whether the current high level of activity represents a persistent evolution or whether it merely marks a passing enthusiasm, to be tempered by the difficulty of the challenges facing the development of generalisation technology. Given the fundamental importance of generalisation in the context of flexible and distributed spatial data handling, however, we expect that a lasting coalition of users, researchers, and vendors will form with a strong interest in and commitment to developing workable solutions.

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