Generalization

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Glossary

Cartographic Generalization A range of techniques applied to ensure optimal portrayal of geographic phenomena according to task (theme and scale).

Cartometric Analysis A set of spatial analysis tools used to make explicit and measure metric, topological, and shape characteristics within and among a set of geographic phenomena.

Map Generalization A process of effectively portraying changing levels of detail among geographic phenomena in order to reveal their various properties.

Model Generalization Selection, simplification, and aggregation of features stored in a database for improved processing, dataset integration, and prior to cartographic generalization.

MRDB A database used to store multiple representations of geographic phenomena (created via the model generalization process).

Scale, Pattern, and Geographic Process

It is not possible to describe a geographic process without reference to ideas of scale. The scale of observation is critical to the discernment of pattern and the identification of various types of relationships implicit among the representation of a set of geographic phenomena. Viewing and analyzing geographic space at various levels of detail is common practice in the geosciences. The activity helps to discern the operational scales of geographic phenomena, the extent and permanence of patterns, which in turn sheds light on the underlying processes and their interactions. The scale of observation scopes the problem – the map acting as a filter and, in a digital context, an interface by which we can further explore attributes of the data. Cross-scale analysis enables us to connect together processes operating across a continuum from the fine scale (large-scale mapping) to the coarse scale (small-scale mapping), and is a start point from which we can theorize about causal processes, and from this, make generalizations about the world, and go on to test and develop predictive models (Figure 1)– the evolution of our models and theories often revolving around the visual form.

The creation of paper map series (typically at scales of 1:10 000, 1:50 000, 1:250 000, 1:500 000) is testament to a requirement that we are able to view the world in an abstracted, thematic form, at various levels of detail, in order to discern fundamentally different (yet connected) properties among a specific set of geographic phenomena. For example, general circulation models help us understand climate change at the global scale. They are (almost by definition) inadequate in helping us to explain subtle regional differences that might point to localized anomalies, yet which collectively contribute to a global effect. Being able to represent geographic phenomena at a range of scales lies at the heart of the cartographic discipline (Figure 2).

Traditionally, the cartographic task was the preserve of the human cartographer. The human acted to interpret the requirements of the user, and produce a paper-based map of high quality – void of ambiguity, often tailored to the expectations of the user. Information technology (IT) has disrupted this relationship, offering, in the first instance, opportunities to support this human process (via computer-aided cartography), but now going further – seeking to emulate the process of design, thus fundamentally changing the role of the cartographer. Beyond this, IT has created a paradigm shift in how we explore geographic data, leading to developments in the field of scientific visualization, in which the digital map acts as a window onto the underlying database, by which we can manage, visualize, and analyze the data.

Not surprisingly, early attempts at automation treated map series products as being quite distinct from one another – reflecting the discrete production process for each of the scales within national mapping agencies (NMAs). This resulted in different databases, representing (in many cases) the same phenomena but at different scales. But a line of thinking soon began to emerge which challenged the wisdom of this redundancy. The question became: could we not store the phenomena once (at a very high level of detail), and then apply a

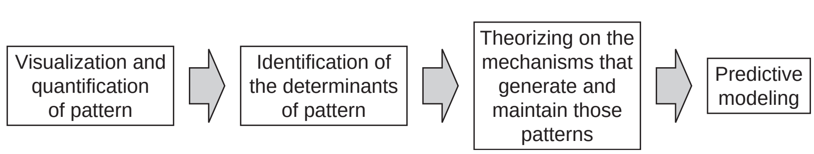

Figure 1 From scrutiny of pattern to predictive statements.

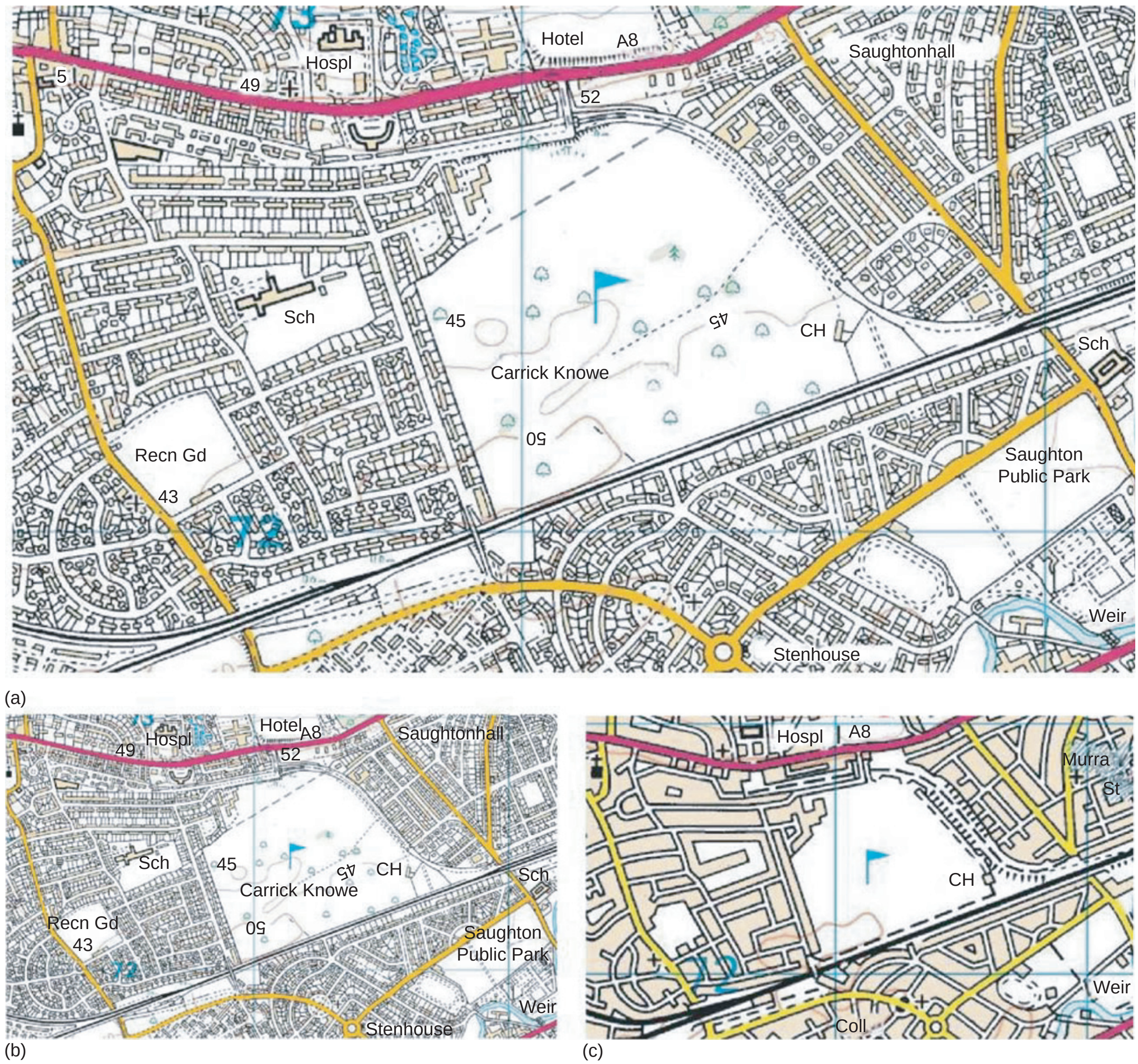

Figure 2 Need of generalization. (a) Source map at 1:25 000, (b) nongeneralized map at 1:50 000, and (c) generalized map at 1:50 000. (Ordnance Survey © Crown Copyright. All rights reserved).

range of algorithms that controlled their selection and representation according to the desired scale and theme?

There were significant benefits to this line of thinking. Maintaining a single database was more cost effective than maintaining multiple databases; a high level of consistency could be maintained between different datasets; duplication of storage could be avoided, thus obviating the need to make multiple updates each time something was changed or added into the geographic landscape; most importantly, it offered the opportunity to integrate data from disparate sources, captured at different scales (or levels of detail).

These benefits were premised on the existence of a set of algorithms that would, with minimum intervention from the user, control selection and representation of geographic phenomena according to a specified scale and theme. The science of 'map generalization' is all about designing such algorithms, algorithms that manipulate and symbolize the geometric primitives stored in the database that represent various real-world phenomena. Map generalization is also concerned with (1) modeling the process of design (how generalized does the map need to become), (2) devising evaluation methodologies by which it can assess the quality of the design solution, and (3) development of interfaces that support users who may well be cartographically illiterate, or who struggle to specify their requirements. We begin by describing the techniques used to manipulate objects within the database. We then describe some of the frameworks designed to support their application in the overall design of the map. The discussion that follows this argues that high levels of automation can only be achieved if the automated environment includes methods of evaluation. The article concludes with a brief discussion of the changing context of map generalization within developing applications (such as exploratory data analysis and location-based services).

Tools and Techniques for Map Generalization

The goal of map generalization is to give emphasis to salient objects and their properties while omitting less-important qualities with respect to the scale and the purpose of a map. We therefore need a system that supports manipulation of map objects and their relationships, and more generally supports the representation of phenomena at different scales. For example, at the finest scale, we might wish to represent each individual building, street light, and pavement that we find within a city. But at a coarse scale, all of this might be subsumed by a single 'dot' (with say, the word 'London' next to it), representing the idea of 'city' in which all those buildings are contained. Therefore, the requirements for a map generalization system are: (1) a database containing some abstraction of the real world, (2) a set of algorithms for aggregating objects in that database (model generalization), (3) a library of symbols with which to render the objects according to various themes, and (4) a set of algorithms focusing on improving the legibility of those symbolized objects (cartographic generalization). The database containing that first abstraction is typically called a digital landscape model (DLM – Figure 3). The DLM might be created by digitizing paper maps or from photogrammetric techniques applied to remotely sensed imagery. Typically, a notional scale is associated with the DLM database though it is perhaps more apposite to talk of the level of detail. Data from the database can be symbolized and visualized directly via cartographic techniques. Alternatively, a database of lower semantic and geometric resolution can first be derived (via model generalization) – creating different digital cartographic models (DLMs – Figure 3) before cartographic generalization techniques are applied to produce different maps (DCMs).

Altering the theme and level of detail enables different phenomena and different properties to be portrayed. Sometimes the emphasis is on precision of location, or of shape (important in the map-interpretation process). In other circumstances, we may wish to emphasize connectivity at the expense of other properties and qualities. Maps of transportation networks (such as the London Underground) are nice examples of the need to emphasize connectivity over geographical location. Irrespective of theme, in all cases a map (digital or paper) reflects a compromise in design – a compromise between

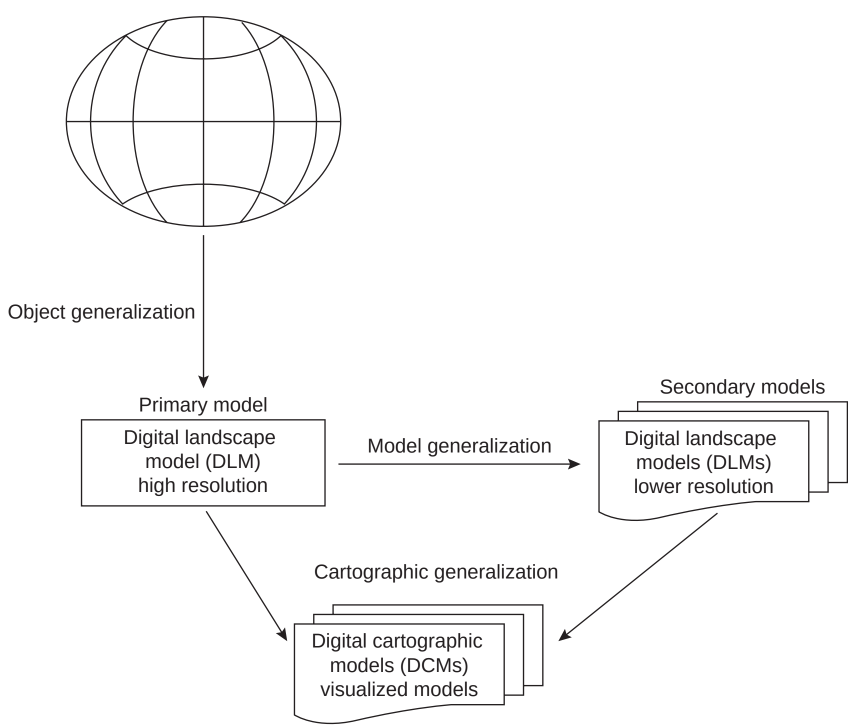

Figure 3 The first abstraction of reality creates the primary digital landscape model (DLM), from which a digital cartographic model (DCM) can be produced – either directly from the DLM or via the process of model generalization and the creation of secondary models (DLMs).

wanting to convey information unambiguously, but not having enough room (given the minimum size of symbology) to show all information. In this sense, the process of design is about making sense of things – the cartographer perhaps working from a mental thumbnail sketch by which their solution reflects the requirements of the user in terms of their need, which in turn govern and constrain the representation of each feature in the map.

Various methodologies have been proposed for trying to capture this design process within an automated environment. Via close observation and interrogation of the human cartographer at work, researchers have distilled out a set of techniques used to manipulate and create more generalized yet recognizable forms of geographic phenomena. Considerable research effort has gone into creating algorithms that mimic these human techniques. These techniques are not applied in isolation, but rather in concert, and in varying degree, across the map, depending on the density of information, the type of phenomenon being mapped, and of course, the theme and scale. Therefore, in addition to algorithms that mimic these techniques, we need some framework in which we can orchestrate this whole design process, and we need some evaluation methodologies that enable us to assess the quality of the solution produced within such a framework. We begin with a review of generalization techniques under the headings of model and cartographic generalization.

Model Generalization

Typically we can divide the techniques under two headings – model and cartographic generalization. The objective of model generalization techniques is to reclassify and reduce down the detail, and give emphasis to entities associated with the broader landscape – thus enabling us to convey the extent of the forests rather than see the trees, or to see the island chain along the plate margin, rather than the individual island. The model generalization process is not concerned with issues of legibility and visualization; is more useful to view it as a filtering process; a set of techniques concerned with (1) selection of phenomena according to theme, and (2) the classification and aggregation of phenomena. Typically, model generalization precedes cartographic generalization; alternatively, model generalization may be required in response to a nonvisual query, or as a prerequisite to data analysis. For example, the question 'what modes of travel exist between the cities of Edinburgh and Glasgow?' requires us first to aggregate together phenomena at the fine scale (in this case dense regions of buildings) in order to define the extent and general location of these two entities. Only then can we identify, for example, the major roads that connect these two urban centers.

Composite or higher-order objects are formed via the processes of thematic and spatial abstraction. In thematic abstraction, the number of distinct attributes of objects in the database is reduced. In spatial abstraction, the number of objects are reduced by means of aggregation or elimination. Thematic abstraction often triggers spatial abstraction. For instance, objects having similar attribute structure can be categorized into classes under the process of classification. Each object then becomes an instance of a particular class and that class defines an object's properties in terms of its attribute structure. If different classes share some attributes, then a superclass or parent class can be created whose attributes are the common attributes of its child classes. This creates a hierarchy where complex classes are present at the detailed low end of a hierarchy and increasingly abstracted classes are present as we go up the hierarchy. This type of hierarchy is called a taxonomy or classification hierarchy (**Figure 4a**). The creation of these hierarchies is an important way of modeling the changing levels of detail and provides a basis for creating the generalized map (**Figure 4b**).

Another complimentary hierarchy useful in the creation of composite objects is a partonomy. Whereas a taxonomy refers to an 'is–a' relationship, a partonomy refers to 'part–of' relationships between parent and child classes – reflecting more of a functional and conceptual division of geographic space. Over large changes in scale, it is necessary to aggregate objects belonging to different classes in order to create composite objects. A prototypical view of a city might be defined as a dense collection of municipal and industrial buildings, and multimodal transportation infrastructures. Once represented in partonomic form, it can be used as a basis for combining objects together – in this case, moving from the detail of the house, land parcel, and pavement, to a simple city block (**Figure 5**and **Figure 2**).

In addition to these techniques of aggregation, there are two other techniques that fall under 'model generalization' – selection and simplification. As the name suggests, selection is the (straightforward) process of selecting a subset of all classes of objects falling within a specified region. The selection process is governed by task, which in turn tends to define the scale and the theme. The long tradition of topographic and thematic mapping often acts as a basis for specifying content, and thus which classes of objects are selected. The other technique is called 'simplification' – and is defined as the process of reducing the number of geometric points used to store the physical location or extent of a geographic object. One can envisage many points being used to record the detail of the outline of a gothic cathedral, or the sinuous path of a low-lying river. The challenge of simplification is to reduce the number of points used to store the representation of such features, but in a way that still conveys their essential shape and location. Successful

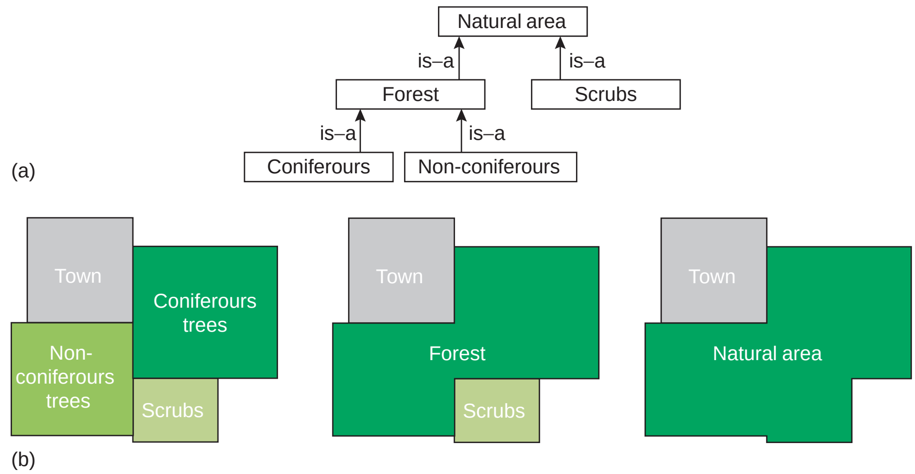

Figure 4 (a) Example of a classification hierarchy, that is, a taxonomy, and (b) class-driven generalization based on that taxonomy.

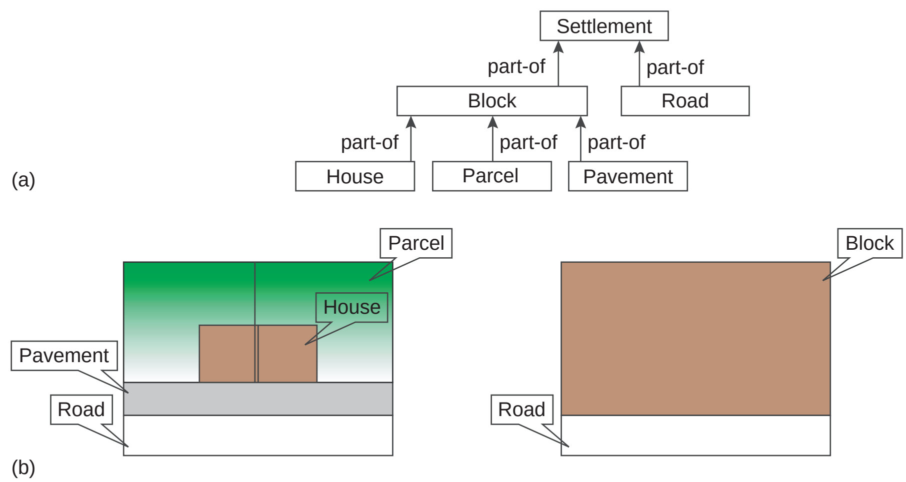

Figure 5 (a) Example of a partonomic structure for settlement, and (b) aggregation of data based on that partonomy.

simplification reduces storage requirements and processing time. Successful algorithms have been those that have identified and retained critical changes in direction (such as the corners of a building, or the main changes in the course of a river) while removing those points that are not critical to conveying the essential qualities of the object (e.g., the extent and angular nature of a building, or the connecting properties of a river to the sea). Once the model generalization process has taken place, the challenge is then to render those objects into some map space (either for paper production, or as part of a digital interactive environment – a desktop or mobile environment).

Cartographic Generalization

Cartographic generalization is a set of techniques concerned with increasing the efficiency with which the map is interpreted – thus the techniques aim to resolve ambiguity, and to retain those qualities of a representation that best fit with the user's expectations. Symbols used to represent spatial objects from the source database must be visible to the naked eye; but as the scale reduces, the amount of space available decreases thus creating competition for space. To retain the clarity and to represent the information effectively, a range of cartographic generalisation techniques are applied such as symbolization, smoothing, simplification, grouping, enhancement, displacement, and text placement (Figure 6).

When we come to apply these techniques (often in combination), they must be applied such that, irrespective of the scale of portrayal, the essential qualities of the feature are still conveyed (that rivers retain their sinuous and connected form, and buildings retain their anthropogenic qualities (such as their angular form)). Different combinations, amounts of application, and different orderings of these techniques can produce different, yet aesthetically acceptable, solutions. The focus is not on making changes to information contained in the database, but upon avoiding ambiguity in interpretation of the image. The process is one of compromise reflecting the long-held view among cartographers that making maps involves telling small lies in order to convey the truth! Figure 7a metaphorically represents the contents of the database. The symbolization and enhancement process has led to overlap (Figure 7b) such that displacement is required (Figure 7c), which has improved the clarity of the map, but at some cost to the locational accuracy of these features.

Analysis, Synthesis, and Evaluation of Cartographic Solutions

For any given cartographic conflict (such as the one presented in Figure 7b), one can envisage a number of viable solutions (of which Figure 7c is just one). The choice of solutions will depend, among other things, on: the number of features, their position relative to one another, and their importance relative to the intended theme. Trying to create viable solutions (synthesis – Figure 8), and then choosing a solution among that choice requires two things: (1) an initial analysis phase in which the conflicts are identified (analysis – Figure 8), and (2) a form of evaluation such that we can assess the quality of the solution (evaluation – Figure 8). Failure to find an adequate solution might either result in further analysis of the conflict or flagging unresolved conflicts and drawing these to the attention of the user.

The analysis phase is akin to the eyes of the cartographer and involves making assessment of the degree of severity of the conflict (extent and complexity and composition). A broad and extensive set of cartometric techniques have been developed to measure the various qualities inherent among the map features. This is because we wish to ensure minimum disruption in those qualities during the cartographic generalization process. For example, an unacceptable solution to Figure 7b would be one that placed the church to the right of the road, or one that significantly distorted the shape of the road. Maintaining adjacency relationships requires the use of Delaunay and Voronoi diagrams (Figure 9) which are ways of exhaustively tessellating the space between geographic features, and making explicit shape and distribution parameters.

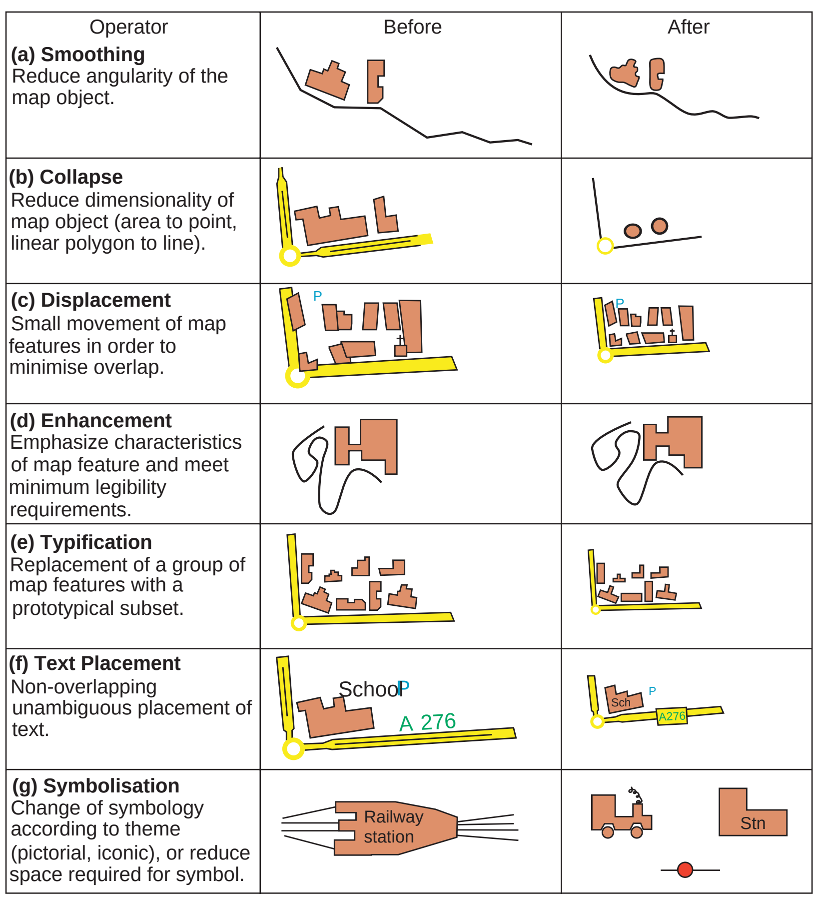

Figure 6 Definition of generalization operator, initial data, and result after application of the technique.

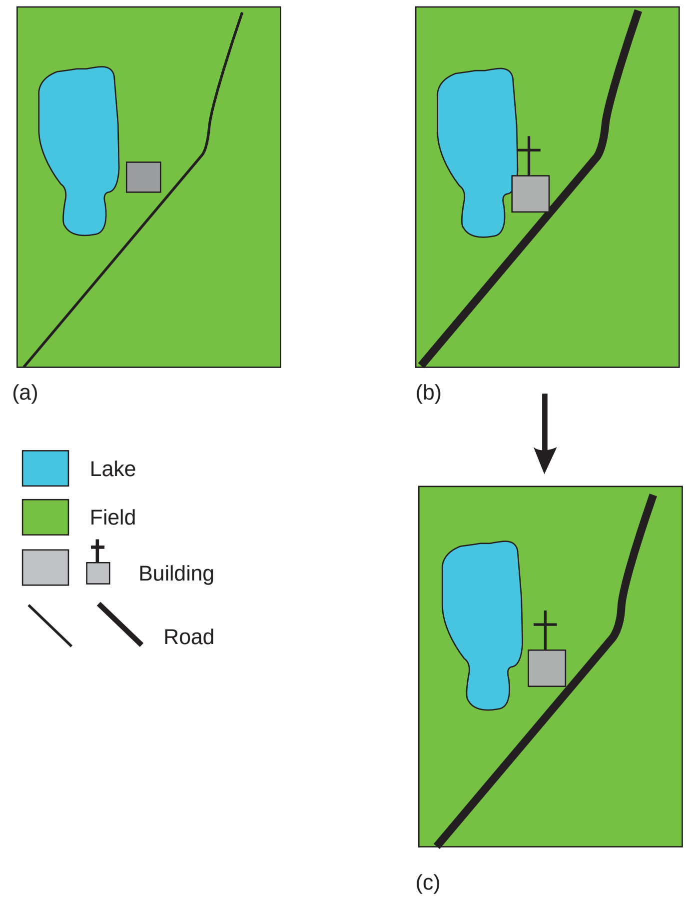

Figure 7 Difference between cartographic and model generalization. (a) Result of model generalization, (b) results of cartographic generalization (symbolization, enhancement, and simplification) has led to overlap, and (c) displacement is needed to remove ambiguity.

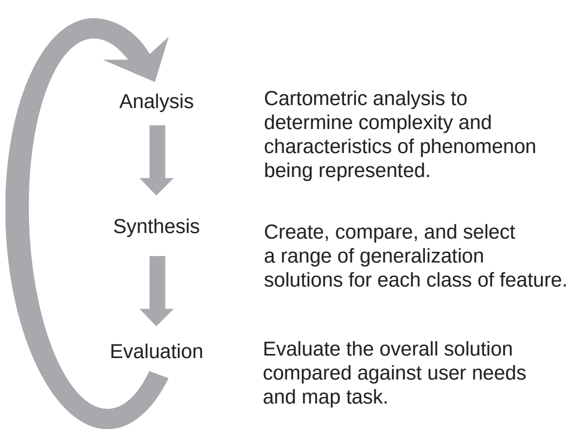

Figure 8 Essential components of a map generalization system: analysis, synthesis, and evaluation.

It might also be necessary to ensure connectivity among features (such as road networks) during the process of generalization. Graph theory is often used to model this process (both in model generalization when selecting subsets of roads and during cartographic generalization) (Figure 10).

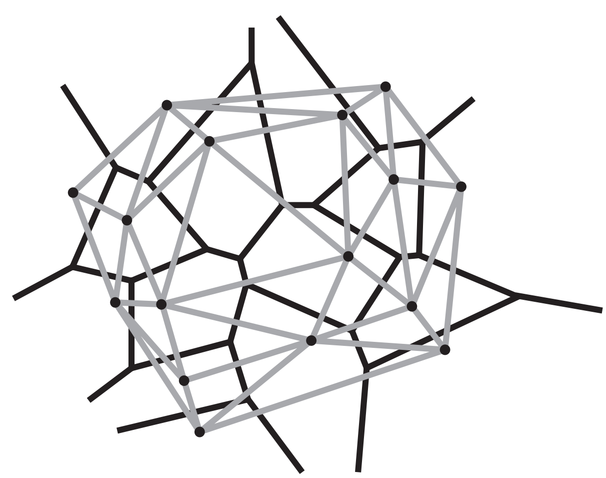

Figure 9 The use of Delaunay (gray) and Voronoi (black) diagrams enables relative proximity and adjacency properties to be measured.

Many other shapes and pattern metrics have been proposed – often applied in the analysis phase, and again in the evaluation phase. If we assume that synthesis involves creating a number of candidate solutions, then the

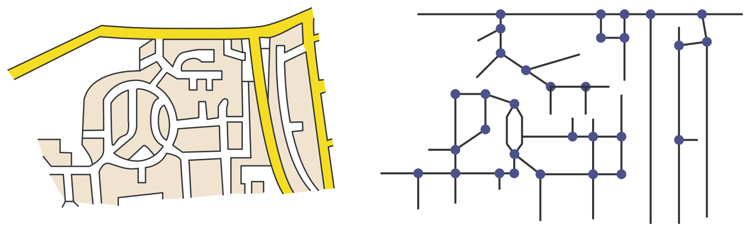

Figure 10 Graph theory can be applied to networks to ensure conservation of connectivity relationships and to control the 'pruning' of networks. (Ordnance Survey © Crown Copyright. All rights reserved).

best solution might be one that has resolved the conflict (improved its legibility), while producing the least amount of change among the various cartometric measures (in terms of topology, area, shape, and distance).

Modeling the Generalization Process

Having a set of techniques for manipulating objects in the database and in the portrayal stage is not, by itself, sufficient when it comes to designing an autonomous map generalization system. The selection and application of techniques, the creation of candidate solutions, and their evaluation requires some framework in which this can all take place. Because of the interdependent nature of geographic phenomena, it is rare that changes can be made without having to consider the broader context. For example, the solution in Figure 7c is only appropriate because there is sufficient space for the objects to be displaced into. If buildings have to be aggregated in one part of the map (perhaps because of the density of features), then for reasons of consistency, this needs to be applied to other occurrences. Procedural and heuristic knowledge needs to be incorporated within these frameworks so that the solutions most likely to be successful can be applied first. Among the various 'frameworks' explored, two are worthy of mention: rule-based approaches, and constraint-based approaches.

Rule-Based Approach

Since the cartographic design process appeared to involve decision making and use of 'rules of thumb', it was assumed that knowledge-based approaches (expert systems) could be used to model the process – using a rule-based approach. These systems used either a predetermined rule execution sequence or an inference engine to control the execution sequence in applying various techniques. They consisted of three main parts: a knowledge base, an inference engine, and a user interface (Figure 11). The knowledge base contained a set of rules, facts, or procedures. The inference engine controlled the generalization process by making use of the rules and procedures in the knowledge base. The user interface contained menus for selecting the datasets and intended

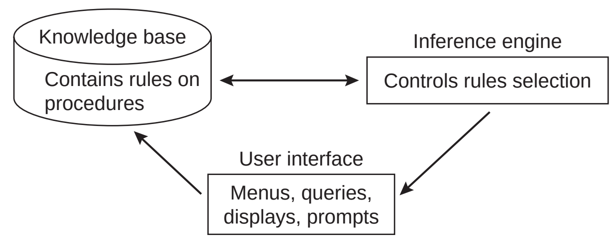

Figure 11 The essential components of a rule-based system.

theme and scale, and a mechanism for adding or updating rules in the knowledge base.

An example rule might be:
If important (building) AND size (building, $< 50\ \mathrm{m}^2$) THEN enhancement (building).

This simple example of a rule captures the idea of cartographically enhancing buildings if they are small yet important to the intended theme. There are examples of partial successes with this approach (the OSGEN system from Ordnance Survey and CHANGE from the University of Hannover), but several weaknesses were identified: it was hard to formulate rules for all the exceptions and circumstances in which a particular conflict might occur, they tended to operate over quite small changes in scale, and for limited classes of features. It was hard for the human to know what the consequences might be for any change or addition made to the rules. It had been assumed that rules could readily be formulated from map specification documents, but solutions were often demonstrated by illustration, and cartography has never devised the syntax or semiotics (a system of signs) that could be used to facilitate the rule formulation process. When cartographers were asked to explain their actions as they worked, they often found it hard to articulate their reasoning and were found to be inconsistent in their application of a technique.

Constraint-Based Systems

More recently, generalization research has focused on a holistic view of the process acknowledging the knock on effects of generalization and the interdependent nature of

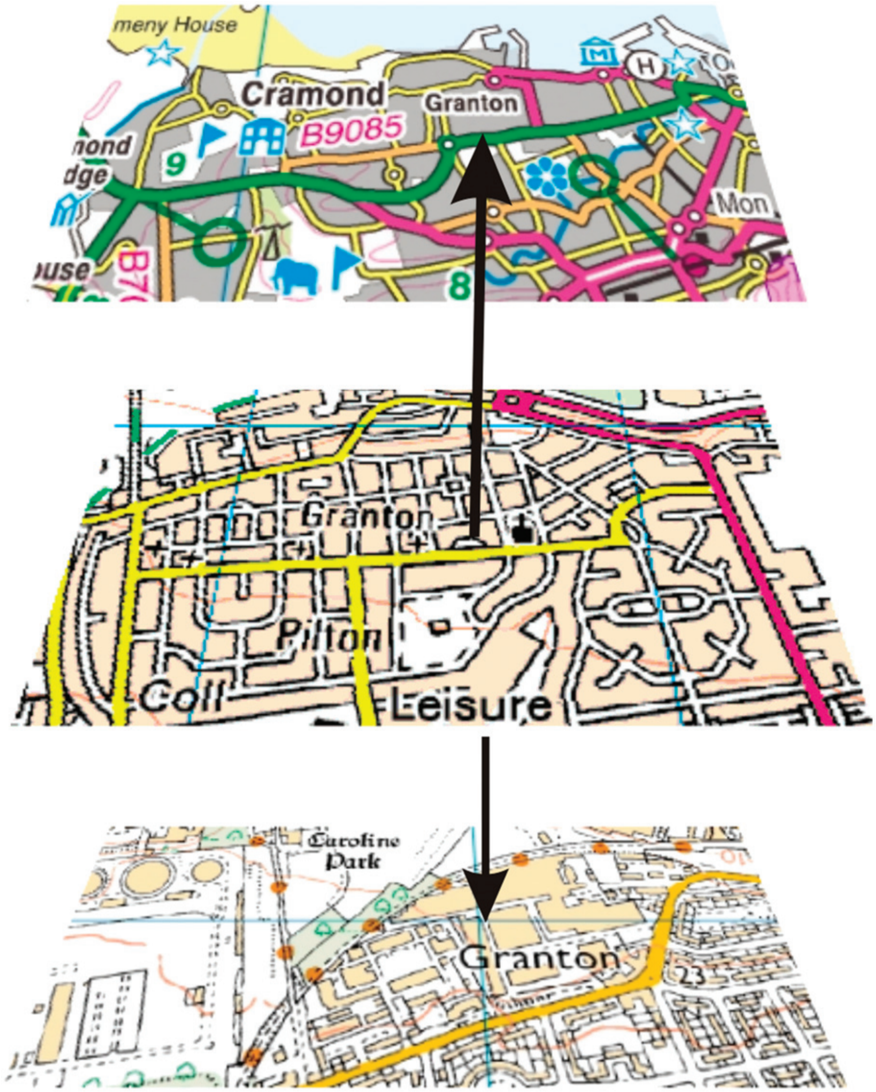

Figure 12 MRDB storing multiple representations of different geographic phenomena. (Ordnance Survey © Crown Copyright. All rights reserved).

the solution. Currently, there is much interest (and promise) in using a constraint-based approach – where the aim is to find a state whereby the maximum number of constraints can be satisfied. In this context, there has been much research effort devoted to agent-based methodologies – in which each object in the database is modeled as an agent – an object-oriented concept in which the object has goals, behaviors, and a capacity to communicate with other agents. These are referred to as 'multi-agent systems'. The goals reflect those of the generalization process – namely to efficiently render the object without ambiguity. The agent makes decisions about its representation based on its own goals while considering the goals and constraints of its neighbors. Ideas have included a hierarchy of agents in which higher-order agents are concerned with broader contexts and distribution of agent classes, while agents at the individual object level are concerned with the specific representation of individual objects. The AGENT project is one project which has been developed into a commercial system that now supports a number of national mapping agencies, notably the National Mapping Agency of France (IGN).

As a corollary to this discussion, by partially incorporating the decision-making process within rule-based and agent-based systems, the balance of decision making has shifted away from the human to the machine. This has presented some real challenges in the design of interfaces that are intuitive to use, allowing the user to specify their mapping requirements in a simple and efficient manner within very complex systems. Researchers have challenged the idea of totally autonomous solutions, arguing that interaction is critical to ensuring that the user remains part of the design process. The idea of semiautonomous generalization techniques, involving the user in critical evaluation tasks reflects a more collaborative approach to design. Coupled with machine learning techniques, this scenario might enable capture of design heuristics – thus gradually improving the sophistication of proffered solutions.

Multirepresentation Databases

For databases potentially containing millions of objects, the processing overheads for even the simplest of generalization tasks is huge. Delivery of digital maps over the Internet, generalized in real time is not currently achievable. The obvious solution is to generalize maps in batch mode in anticipation of demand, or at least store in the database multiple generalized representations of each object, or groups of objects. This has given rise to the idea of multirepresentational databases – databases that explicitly store objects in different generalized states, such that generalization is more of a selection and compositional process – bringing together different classes according to scale and theme (**Figure 12**).

The data model must connect together these different representations such that when changes are made in the primary DLM, these changes can be automatically reflected among the more generalized versions of the object. This same hierarchical structure can then be traversed according to the intended level of detail as the user zooms in and out.

Conclusion

When we look at maps at different levels of detail or scale, it is not that we see 'less' information but that we see 'different' information. The aim of generalization is to support this process – to give emphasis to attributes and relationships at the broader scale. Attempts at automation have revealed just how challenging and creative the art and science of cartography is. Developments in visualization methodologies have not obviated the need for generalization methodologies that abstract geographic space in order to reveal the patterns and interdependencies inherent among geographic features.

See also: Geovisualization; GIS and Cartography; Maps; Mapping, Distributed; Spatial Databases.

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