

## Encyclopedia of Geographical Information Science

### TITLE

#### 214 Symbolization and Generalization

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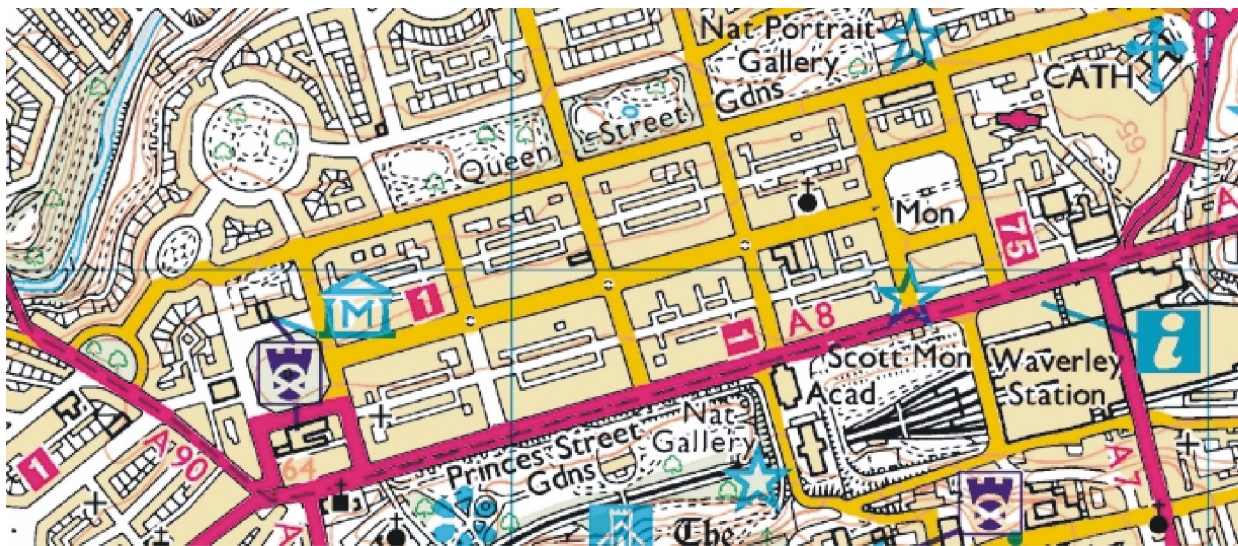
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### SYNONYMS

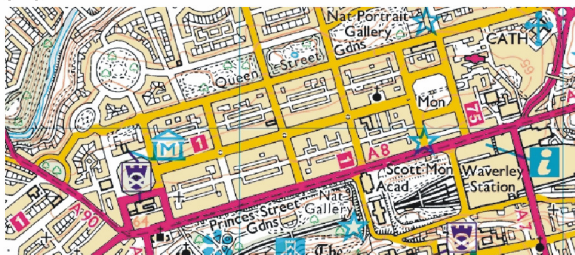
Model generalization, cartographic generalization, map generalization

### DEFINITION

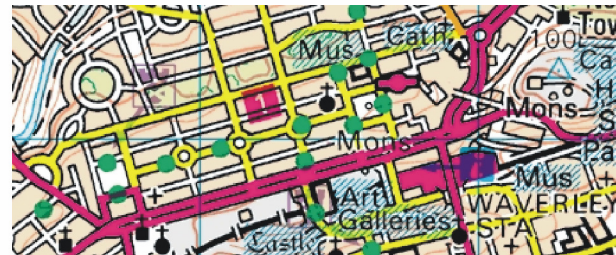
Map generalization is a process concerned with the application of a set of algorithms to geographic data (represented in vector form) in order to control the optimal representation of geographic phenomenon at a range of different scales or levels of detail. In that sense, generalization seeks to mirror the process of map design previously undertaken by the human cartographer. In the context of geographical information systems (GIS), this process is modeled as two sets of operations: the first is a set of database operations (model generalization) and the second is a set of visualization operations (cartographic generalization). Model generalization is concerned with simplifying the representational form in order to achieve efficiencies in data storage, selecting classes of objects according to some specified scale and map theme, and aggregating groups of objects in accordance with scale constraints. Cartographic generalization (a compliment to model generalization) is concerned with the optimal portrayal of those selected and aggregated features. Cartographic generalization involves selecting appropriate symbols, giving emphasis to some of the feature's defining characteristics, and where there are dense regions of features, omitting some features or making small displacements to features in order to resolve ambiguity. Figure 1 seeks to demonstrate the need for generalization. Simple photographic reduction is not sufficient (Figure 1b); thus the aim of map generalization is to derive smaller scale mapping (Figure 1c) from detailed, large scale mapping (Figure 1a).



(a)



(b)



(c)

Figure 1: Map generalization – creating different geographies of space. (Mapping is Ordnance Survey ©Crown Copyright. All rights reserved).

## HISTORIAL BACKGROUND

‘All geographical processes are imbued with scale’ [1:214], thus issues of scale are an essential consideration in geographical problem solving. The scale of observation governs what phenomena can be viewed, what patterns are discernible, and what processes can be inferred. Study in the geosciences is focused both on the detail of those phenomena, as well as the broad linkages across regional and global space. Choosing scales of analysis, comparing output at different scales, describing constructions of scale [2] are all common practices in the geosciences. Traditionally it has been the cartographer’s responsibility to select a scale, to symbolize the phenomena, and to give meaning through the addition of appropriate contextual information. Historically the paper map reflected the state of geographical knowledge, and was the basis of geographical inquiry. Indeed it was argued that if the problem ‘cannot be studied fundamentally by maps – usually by a comparison of several maps – then it is questionable whether or not it is within the field of geography’ [3:249]. Information technology has not devalued the power of the map, but it has driven a series of paradigm shifts in the storage, representation and interaction with geographical information. Early work in automated mapping focused on supporting the activities of the human cartographer who remained central to the map design process. Current research is focused more on ideas of autonomous design – systems capable of selecting optimum solutions among a variety of candidate solutions delivered over the web, in a variety of thematic forms, in anticipation of users who have little or no cartographic skill. Historically the paper map reflected a state of knowledge. Now it is the database that is the knowledge store, with the map as the metaphorical window by which geographic information is dynamically explored. In these interactive environments, the art and science of cartography is being extended to support the integration of distributed data collected at varying levels of detail, whilst conforming to issues of data quality and interoperability. With respect to map generalization, the challenge is in developing a set of algorithms and methodologies that mirror the service traditionally provided by the human cartographer, yet takes advantage of the

paradigm shift afforded by information science in interacting with, and exploring geographic information.

### **SCIENTIFIC FUNDAMENTALS**

The human cartographer provides a service that involves interpreting the requirements of the user, creating and executing a design to a very high quality and clarity according to a theme and scale, and one that is void of ambiguity. Over the past thirty years huge advances in database technology, together with developments in geo-visualization [4, 5] and interactive and web based mapping has disrupted and further displaced the role of the cartographer. The digital map now acts as a window by which we search and explore the underlying database, and the cartographer has supposedly been replaced by symbol libraries and color ramps that facilitate ‘the creation of cartographic monstrosities with unprecedented ease’ [6].

Within this paradigm shift, the requirement to view the world at different scales (or multiple levels of detail) has remained, as has the requirement to produce high quality cartographic products. Initially paper maps at different scales were digitized and stored in different databases. However there is huge redundancy in this model as changes in the real world have to be reflected in changes in each of the databases. A new line of thinking has emerged which asks whether it is possible to store the phenomenon once (at a very high level of detail), and then apply a range of algorithms in order to control the selection and representation of the phenomenon in a form appropriate to the intended scale. There are significant benefits to this line of thinking; maintaining a single database is more cost effective than maintaining multiple databases; a high level of consistency can be maintained between different datasets; duplication of storage can be avoided thus obviating the need to make multiple updates across separate databases each time a change occurs in the real world. Most importantly it offers the opportunity to share data, enabling integration of data from disparate sources, captured at different levels of detail.

These benefits are premised on the existence of a set of algorithms that can, with minimum intervention from the user, control the selection and representation of geographic phenomenon 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. Map generalization can also be viewed as a service that anticipates users unfamiliar with cartographic concepts, and with poor evaluation skills. Such a service must contain the following components: a database capable of storing multiple representations of geographic phenomena, a set of model and cartographic generalization techniques to create such multiple representations, and design heuristics that govern the appropriate choice and sequencing of generalization techniques. The evaluation of any candidate design requires the system to create alternate candidate designs (synthesis), and to evaluate and select the best solution (which in turn requires a set of cartometric analysis tools). Interpreting the map requirements of the user, and presenting solutions in response requires an interface that can ‘translate’ straightforward requests into rich specifications and parameter setting. These are deemed to be the essential components of a Map Generalization Service (Figure 2).

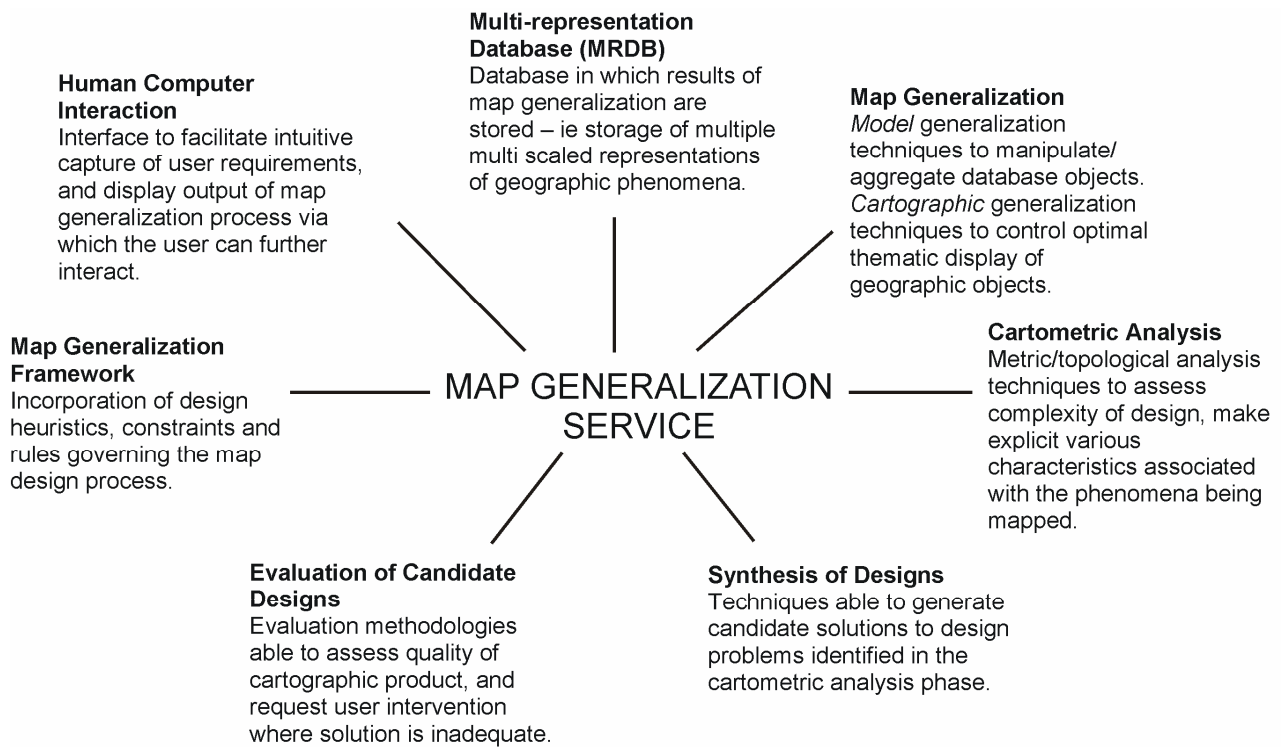


Figure 2: The components of a Map Generalization Service.

This chapter begins by describing the techniques used to manipulate objects within the database. It then describes 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 entry concludes with a brief discussion of the changing context of map generalization within developing applications (such as exploratory data analysis and location based services).

## 1.2 Tools and Techniques for Map Generalization

The goal of map generalization is to give emphasis to salient objects and their properties whilst omitting less important qualities with respect to the scale and the purpose of a map. Therefore a system is needed 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 each individual building, street light and pavement might be represented. 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) [7]. 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 more apposite to talk of 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 (DCM – Figure 3) before cartographic generalization techniques are applied to produce different maps.

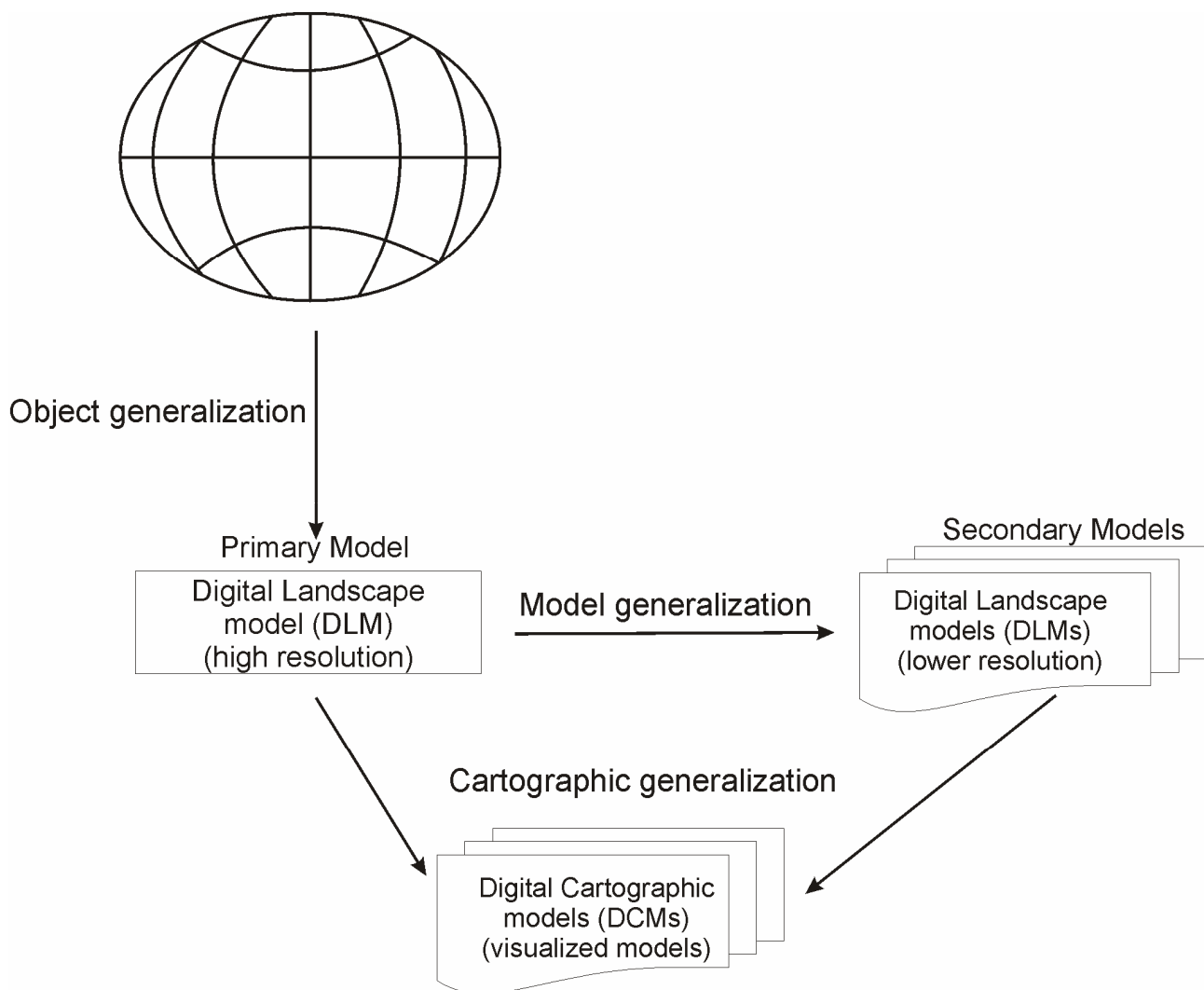


Figure 3: DLM, DCM, Model and Cartographic Generalization.

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, the emphasize may be on connectivity at the expense of other properties and qualities. Maps of transportation networks (such as the London Underground) are a nice example 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 wanting to convey information unambiguously but not having enough room (given the minimum size of symbology) to show all that 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.

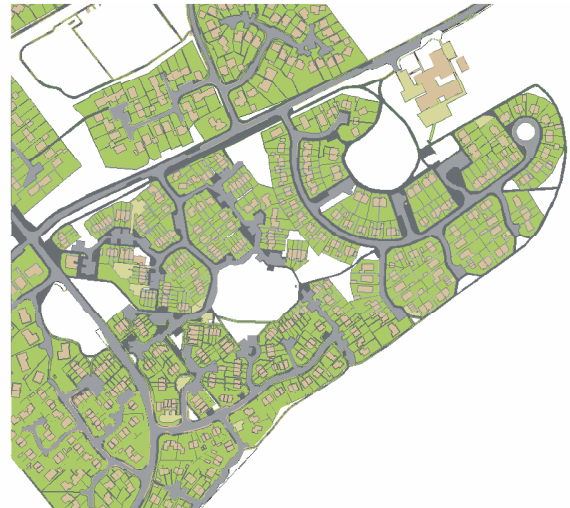
Various methodologies have been proposed that try to capture this design process within an automated environment. Considerable research effort has gone into creating algorithms that mimic these human techniques. These techniques are not applied in isolation, but rather in concert, and in varying degree, across the map, depending on the density of information, and the type of phenomenon being mapped, and of course, the theme and scale. Therefore in addition to algorithms that mimic these techniques, a framework is required that can orchestrate this whole design process, together with some evaluation methodologies required 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.

### 1.2.1 Model generalization

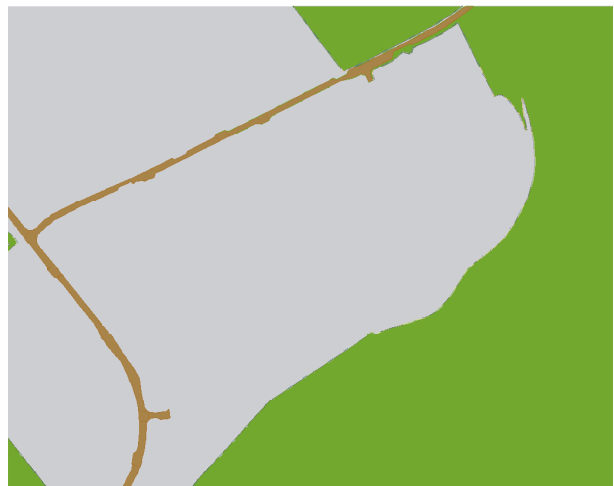
The objective of model generalization techniques is to reclassify and reduce down the detail, thus giving emphasis to entities associated with the broader landscape – thus enabling us to convey the extent of the forests rather than see the trees, or to see the island chain along the plate margin, rather than the individual island. The model generalization process is not concerned with issues of legibility and visualization. It is more useful to view it as a filtering process; a set of techniques concerned with 1) selection of phenomenon according to theme, and 2) the classification and aggregation of phenomenon. As the name suggests, selection is the (straightforward) process of selecting a subset of all classes of objects falling within a specified region (Figure 4). The selection process is governed by task, which in turn tends to define both the intended scale and 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.

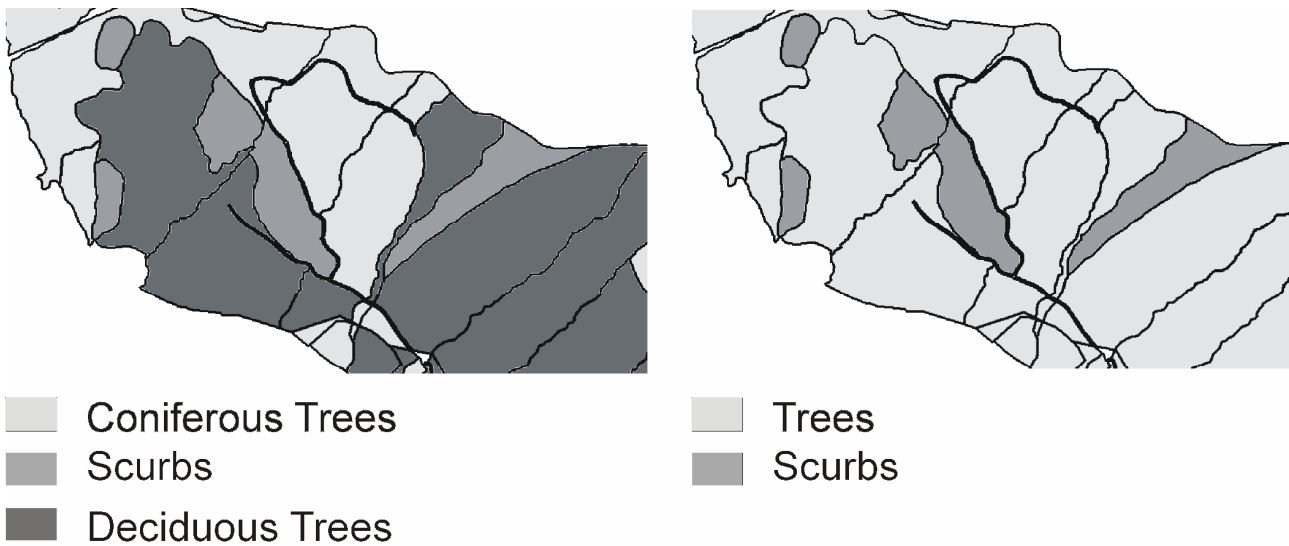


(a)



(b)





(c)  
 Figure 4: (a) Selection, (b) Aggregation and (c) Classification. (Mapping is Ordnance Survey ©Crown Copyright. All rights reserved).

Typically model generalization precedes cartographic generalization. It may also be required in response to a non-visual 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 that we first 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 the major roads connecting these two urban centers be identified.

Composite or higher order objects are formed via the process 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 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 super class or parent class can be created whose attribute 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 one goes up the hierarchy. This type of hierarchy is called a taxonomy or classification hierarchy (Figure 5) and can be used as a basis for classification of data (‘classification’ Figure 4).

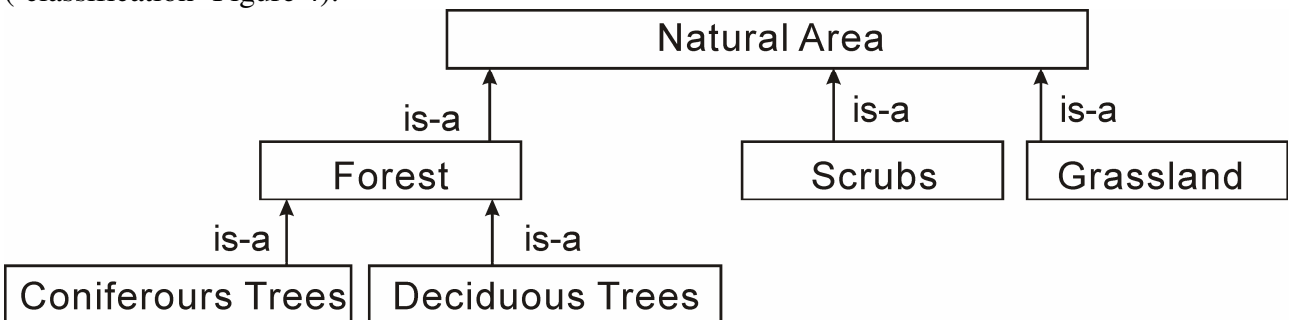


Figure 5: Example of a taxonomy.

Another complimentary hierarchy useful in the creation of composite objects is a paratomy. Whereas a taxonomy refers to a ‘is-a’ relationship, a paratomy refers to ‘part-of’ relationships between parent and child classes – reflecting more of a functional and conceptual division of geographic space (Figure 6) [8]. Over large changes in scale it is necessary 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 multi modal transportation infrastructures. Once represented in partonomic form, it can be used as a basis for combining such objects together ('aggregation' Figure 4).

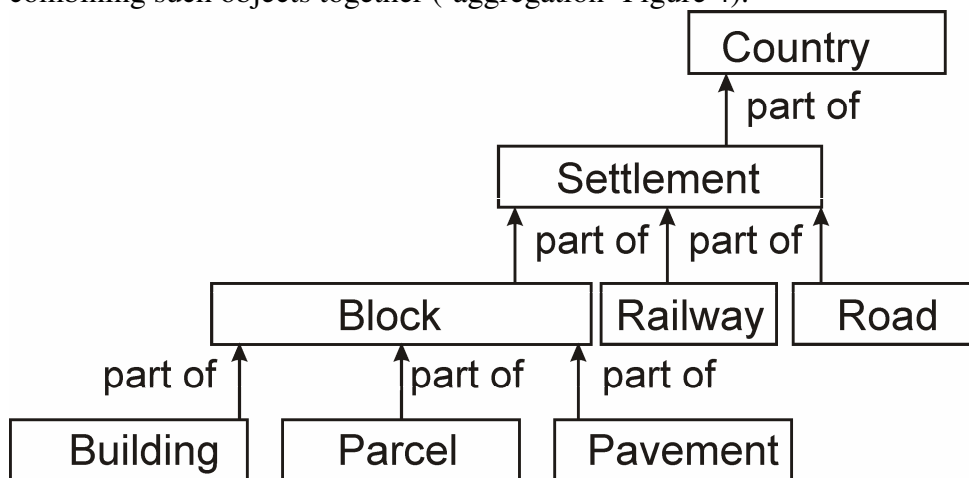


Figure 6: Example of a partonomy.

In addition to the techniques of selection and aggregation, there is '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 simplification reduces storage requirements and processing time. Once the model generalization process is completed, the challenge is then to render those objects into some map space (whether it is for paper production, as part of a digital interactive environment – in either a desktop or mobile environment).

### 1.2.2 Cartographic Generalization

Cartographic generalization involves symbolizing the selected data, and applying a set of techniques that optimally convey the salient characteristics of that data, including careful placement of associated text. Symbols used to represent spatial objects from the source database need to be visible to the naked eye. As the scale reduces the amount of space available decreases thus creating competition for space among the symbology. To retain the clarity and to represent the information effectively a range of techniques are applied such as symbolization, smoothing, simplification, grouping, enhancement, displacement, and text placement (Figure 7).

Operator	Before	After
(a) <b>Smoothing</b> Reduce angularity of the map object.		
(b) <b>Collapse</b> Reduce dimensionality of map object (area to point, linear polygon to line).		
(c) <b>Displacement</b> Small movement of map objects in order to minimise overlap.		
(d) <b>Enhancement</b> Emphasize characteristics of map feature and meet minimum legibility requirements.		
(e) <b>Typification</b> Replacement of a group of map features with a prototypical subset.		
(f) <b>Text Placement</b> Non overlapping unambiguous placement of text.		
(g) <b>Symbolization</b> Change of symbology according to theme (pictorial, iconic), or reduce space required for symbol.		

Figure 7: Cartographic generalization operations.

These techniques (often applied in combination), seek to give prominence to the essential qualities of the feature portrayed (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 is solely focused upon avoiding ambiguity in the 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 tell the truth!

### 1.3 Analysis, Synthesis and Evaluation of Cartographic Solutions

For any given cartographic conflict, one can envisage a number of viable solutions. The choice of solutions will depend on: the density of features, their position relative to one another, and their

importance relative to the intended theme. Trying to create alternate viable solutions (synthesis), and then choosing a solution amongst that choice requires two things: 1) an initial analysis phase in which the conflicts are identified (analysis) and a form of evaluation such that the quality of the solution can be assessed (evaluation). 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 a set of map objects. This analysis is required because we wish to ensure minimum disruption in those qualities during the cartographic generalization process. Many shape and pattern metric techniques have been proposed to measure and minimize the effects of cartographic generalization [9, 10]. These are often applied in the analysis phase, and again in the evaluation phase. The best solution among a set of candidate solutions might be the one that has resolved the conflict (improved its legibility), whilst producing the least amount of change among the various cartometric measures (in terms of topology, orientation, area, shape and distance).

#### **1.4 Modeling the Generalization Process**

The selection and application of generalization techniques, the creation of candidate solutions and their evaluation requires an encompassing. Because of the interdependent nature of geographic phenomenon, 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 in other similar instances. 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.

Since the cartographic design process involves decision making and heuristics (‘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. 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 supported the process of data selection and a mechanism for adding or updating rules in the knowledge base[11].

More recently generalization research has focused on an holistic view of the process acknowledging the knock on effects of generalization and the interdependent nature of the solution. Currently there is much interest (and promise) in using constraint based approaches – where the aim is to find a state whereby the maximum number of constraints can be satisfied. In this context, much research effort has been 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 whilst 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, whilst agents at the individual object level are concerned with the specific representation of

individual objects. The AGENT [12] 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). Figure 8 shows the result from the Carto2001 project [13].

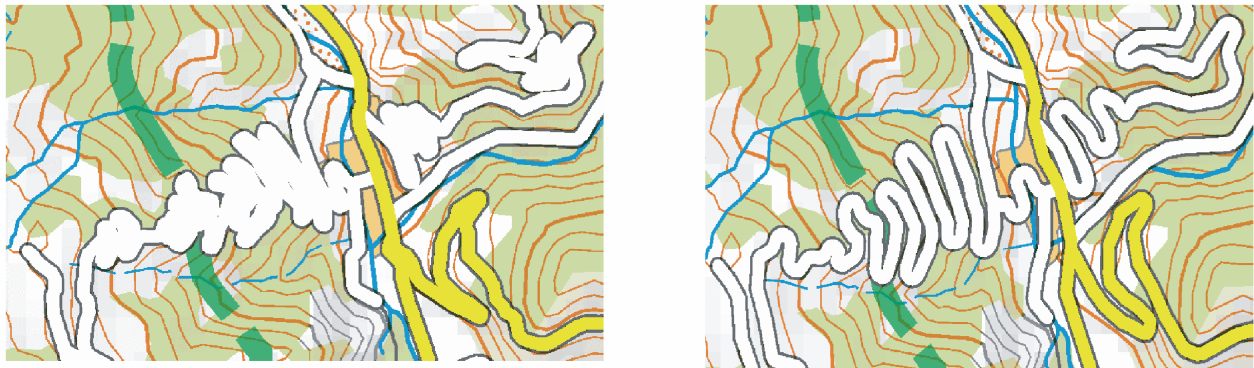


Figure 8: Example output from the IGN's agent based system.

By partially incorporating the decision making process within both 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 very much part of the design process. The idea of semi autonomous 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.

## KEY APPLICATIONS

The idea that map generalization is some 'cartographic end process' belies its importance in supporting five key activities:

### **Cartographic Assistant:**

The existence of many different generalization techniques means that a 'cartographic toolbox' is available for use by a trained cartographer. Research efforts have yielded a set of algorithms able to analyze map content, and to consistently generalize classes of objects in clearly defined ways. In this collaborative environment, such systems have the capacity to improve the quality of cartographic training, ensure quality control in the design process and enable refinement in the adjustment of parameters used to control generalization techniques.

### **Map generalization service**

In the absence of the cartographer, and in the context of GIS, users (with limited cartographic knowledge) require assistance in the rapid design and delivery of cartographic products – often via the Internet, that can vary in theme and scale according to task. Completely autonomous solutions (with no user intervention) have proved to be impossible to design, but in any case are not desirable where meaning is often derived through interaction and exploration of the data. The idea of a map generalization service is that maps can be delivered over the Internet in response to user request – which in turn has led to a focus on the pre-processing of solutions, in which intermediate solutions are stored in a multiple representation database (MRDB).

### **Populating Multiple Representation Databases**

There currently exist multiple, often disconnected 'silo' databases containing data at different levels of detail. The vision is that model generalization techniques are applied to data captured at the finest

detail in order to create a hierarchical framework of increasingly aggregated geographic phenomena (from house, to suburb, to city to region, to country) – in effect a semantically indexed structure from which different scale linked phenomena can be extracted and queried. The benefit of this approach is consistency and ‘lineage’ (provenance) by which the source objects from which the higher order geographies have been created can be identified. This can support both data integration, and hugely facilitate the data update process. The existence of MRDB can also support on-the-fly generalization and instantaneous delivery of geographic data over the Internet and mobile devices [14, 15]

### **Spatial Data Integration service**

Considerable ‘value add’ comes from the sharing and integration of data. Integration of geographic data is beset by a host of challenges receiving considerable attention – notably in development of shared data schemas, and addressing ontological issues linked to culture, original purpose and conceptual understandings of place. Many of these issues relate to the notional scale at which the data was originally captured. Model generalization techniques can play a critical role in aggregating data according to shared paronomic and taxonomic classification methodologies.

### **FUTURE DIRECTIONS**

Generalization in the context of geographical information science has an importance beyond traditional cartographic lines. It has everything to do with revealing and giving emphasis to properties inherent among geographic phenomenon – and therefore has important cross over with ideas of design (making sense of things), data mining and geo-visualization [16]. The aggregation of phenomenon is dependent on taxonomic and paronomic hierarchies, which themselves reflect complex functional and contextual interdependencies inherent among geographic phenomenon. In this sense, issues of generalization are central to meaningful interrogation and analysis of all geographic information.

### **CROSS REFERENCE**

4	Adaptive visualization for mobile usage
5	Agent communication models
262	Data generalization
29	Data warehousing and GIS
39	Effects of scale
48	Exploratory Visualization
62	Geospatial data conflation
72	Hierarchies, levels of detail
74	Hierarchical spatial models
115	Map Generalization
145	On-the-fly generalization
151	Personalized maps
192	Spatial Data Analysis
235	Web mapping

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