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A MULTI-SCALE DAG FOR CARTOGRAPHIC OBJECTS*¹

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ABSTRACT

Geographic Information Systems manage data with respect to spatial location and that data is presented graphically as a map or sketch. A database of objects with some geometric properties is used to render these objects graphically for different tasks. Typically these tasks require graphical presentations at different levels of detail, ranging from overview screens to detailed views [Herot *et al.*, 1980]. Practically a base map is stored and its scale changed graphically. Without major distortions, only changes to twice or half the original scale are feasible by simple numeric scale change. A function to draw cartographic sketches quickly and in arbitrary scales is needed. We propose a multi-scale hierarchical structure where renderings of spatial objects with increasing detail are stored: a directed acyclic graph (DAG). These are used to compose a topographic map at a particular scale. We assume that the object renderings for the DAG already exist. Methods to select objects for rendering are based on the importance of the object for a particular task and on the principle of equal information density. We propose a method for determining information density, namely measuring the ink content of the map.

1. INTRODUCTION

1.1. Motivation

The traditional view of the cartographic process considers three different models and two transformations which lead to the production of a visual map (Fig. 1). There is first the model of the world (e.g. a GIS), consisting of objects with descriptive data.



Fig. 1: Traditional cartographic process

From this model, a subset of the objects is selected to be included in a map, resulting in the set of display objects. These objects are then transformed from a geometrical description to a graphical form, applying rules for symbolization and other aspects of graphical encoding producing the set of cartographic objects. This viewpoint includes usually a strong feedback from the graphical rendering.

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The traditional view assumes that the database contains the objects at highest resolution and that procedures exist to reduce them in scale and correspondingly in detail etc. (Beard). The selection step is first applied and the resulting objects then generalized to the desired level. This calls for automated generalization, a still difficult problem. Efforts to achieve automatic cartographic generalization were successful for specific aspects [Freeman, and Ahn, 1987; Powitz, 1993; Staufenbiel, 1973], but no complete solution is known, nor are there any expected within the immediate future. Buttenfield and McMaster give a comprehensive account of current research trends [Buttenfield, and McMaster, 1991]. This proposal stores object representations for multiple scales in the database and applies only the selection step automatically (Fig. 2), reversing the order of steps.

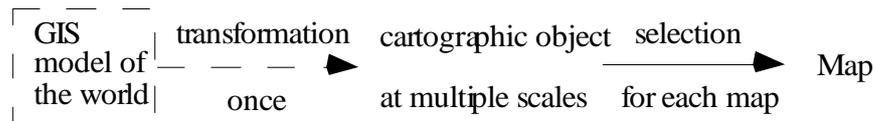


Fig. 2: The proposed selection process

The database will not be much larger than the most detailed database assumed in current proposals (assume that every more generalized representation is a quarter the size of the previous one, then the total storage requires only one third more capacity than the most detailed data set). Generalized representations can be collected from existing maps or for some cases produced automatically.

The transformation of an entity to a cartographic object in this proposal includes the generalization techniques of simplification, aggregation, symbolization and exaggeration (enhancement). The selection technique is explicitly mentioned in the process, whereas the displacement technique has to be considered when placing the objects in the map [Bundy, Jones, and Furse, 1994]. This also implies a feedback from composing the map to the selection technique.

1.2. Proposal

The approach selected here is to construct a multi-scale cartographic DAG (directed acyclic graph), where renderings for cartographic objects are stored at different levels of detail. The output map is constructed as a top-down selection of pre-generalized cartographic objects, till sufficient level of detail is achieved. We assume that the pre-generalized objects are given. Methods to select objects for rendering are based on the principle of equal information density. The dominant operation is 'zoom', intelligently replacing the current graphical representation with the more detailed one, that is appropriate for the selected new scale. We propose a relatively simple method to achieve equal information density, namely measuring 'ink'. The ink content can be determined by counting the number of black pixels per total pixels in the map.

The structure of the multi-scale DAG is based on a trade-off between storage and computation, replacing all steps which are difficult to automate by storage, which would be redundant if automatic deduction were feasible. The resulting DAG structure is more complex than the hierarchical structures proposed in the literature so far [Samet, 1989] since objects can change their appearance considerably e.g. from a single object to a group of objects. These different types of changes are used to derive the structure of the DAG.

The paper is structured as follows: first we examine the different types of changes in object renderings that can occur during scale changes. Then we derive the structure of the multi-scale DAG. After this we explain the selection process and the principle of equal information density. The paper closes with some remarks on further studies.

2. STRUCTURE OF THE MULTI-SCALE DAG

2.1. Types of changes

The multi-scale DAG extends ideas of hierarchies or pyramids and is related to quad-trees [Samet, 1989] and strip-trees [Ballard, 1981]. The DAG structure is more complex than the hierarchical structures proposed in the literature so far, as objects may change their appearance as shown in Table 1. Hierarchical subdivision of special object classes has been dealt with and studied extensively. Strip trees or a very similar design could be used to deal with lines which remain lines over multiple levels. Areal features can be represented by quad-trees as long as they remain areal features. But the multi-scale DAG must also include more dramatic changes. We examined changes that occur during 'zooming into' a representation.

continuous changes	discrete changes		
	slight change	complete change	appears
1. no change in appearance	3. change in symbol	6. change in dimension	9. appears
2. increase of scale	4. increase of detail 5. appearance of label	7. shift to geometric form 8. split into several objects	

Table 1: Types of changes of object representations for smaller to larger scale

The table demonstrates that objects may change their spatial appearance in the generalization hierarchy. A particular problem is posed by objects which are not represented at small scale and seem to appear as one zooms in (type 9).

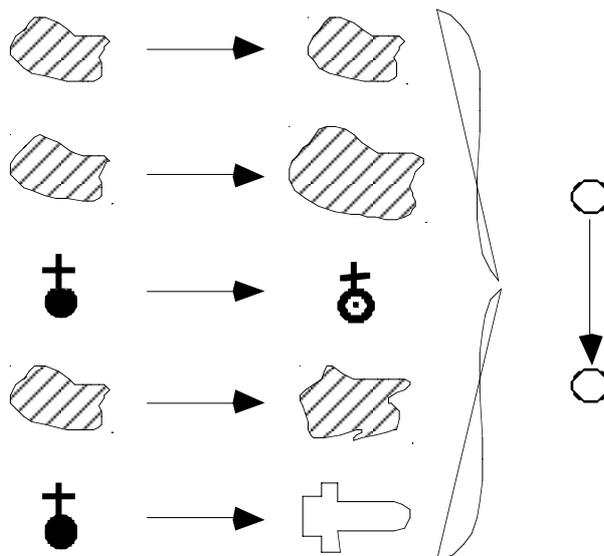


Fig. 3: Examples for the types 'no change', 'increase of scale', 'change in symbol', 'increase of detail', and 'shift to geometric form'

In figure 3, examples are shown for several of the types mentioned in table 1. These changes map to a representation in the DAG, which is shown on the right hand side of figure 3. It is the simplest of all mappings in the DAG, namely from one object representation to another (circles represent nodes with graphical output, pointers represent links between nodes).

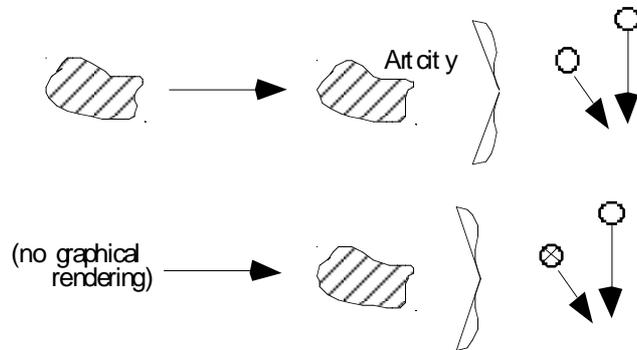


Fig. 4: Examples for the change 'appearance of label' and 'object appears'

The appearance of a label and of an object require an additional branch coming into the DAG-structure. Whereas the label is there and could be shown, a representation of the appearing object does not exist (crossed circles).

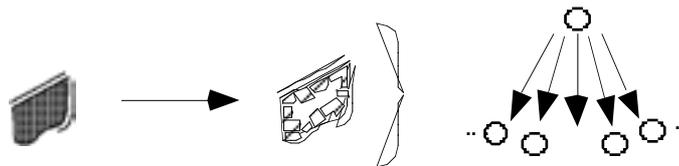


Fig. 5: Example for the change 'split into several objects'

An object, that is split into several objects, requires several links going into the more detailed level in the DAG structure.

Each type of change can be associated with an operation. It is interesting to note, that those operations have inverse operations, which are highly ambiguous. We first defined the changes for zooming in before looking at the changes for generalizing.

2.2. Hierarchical structure

The proposed multi-scale DAG is a method to produce maps of different scales from a single database [Beard, 1987]. It avoids the known problems of cartographic generalization, which cannot be fully automated today, using redundancy. Objects are stored in different levels of generalization, assuming that at least for the difficult cases, the generalization is done by humans, but only once. Building a multi-scale DAG is probably a semi-automated process where automated processes are directed by a human cartographer. All operations where human time is necessary are done once only and the results are stored.

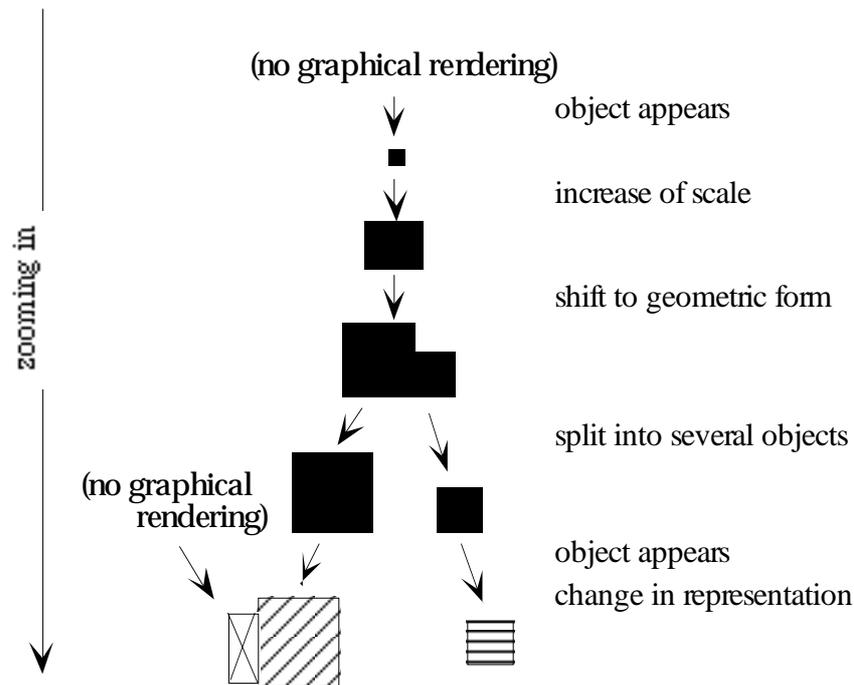


Fig. 6: A multi-scale DAG for buildings

In Graph theory, the structure of a DAG is well known [Perl, 1981]. Applied to our present problem, a multi-scale DAG for buildings might look like the DAG in Fig. 6. While zooming in different changes occur to the representation of the object and affect the structure of the DAG.

It is necessary to note that there will be several DAGs: Traditionally, changes in the map should occur in a certain order [Hake, 1975], namely rivers, railroads, roads, settlements, symbols; areal features, labels. For each of these object groups a different DAG is necessary.

3. MAP COMPOSITION

3.1. Selection of objects

The operation applicable to every node of the DAG is a 'rendering' operation, which transforms the geometric data into a graphical picture. The problem to address is the selection of the objects in the DAG which must be rendered. Two aspects can be separated, namely,

the selection of objects which geometrically extend into a window and
the selection of objects to achieve a constant information density.

The selection of objects which extend into the window is based on a minimal bounding rectangle for each object and a refined decision that can be made based on object geometry. In order to assure fast processing in the multi-scale DAG, the minimal bounding rectangles must be associated with the DAG and DAG branching, such that complete sub-DAGs can be excluded based on window limits. This is well known and the base for all data structures which support fast spatial access [Samet, 1989].

The interesting question is, how the depth of descent into the DAG is controlled to achieve an equal information density. In data structures for spatial access, an 'importance' characteristic has been proposed [Frank, 1981; Van Oosterom, 1989]. It places objects which are statically assessed as important higher in the DAG and they are then found more quickly. The method relies on an assessment of the 'importance' of each object, which is done once,

when the object is entered into the cartographic database. When a cartographic sketch is desired, from this ordered list the most important objects are selected for rendering.

The usability of this idea is currently being studied for a particular case, namely the selection of human dwellings (cities) for inclusion in a map [Flewelling, and Egenhofer, 1993]. A method based on an ordering of objects is not sufficient for the general case. It lacks provisions to deal with multiple representations of objects and must be extended for a multi-scale DAG, which is designed to deal with multiple representations of the same objects. It is also clear, that the ordering of objects is dependent on the purpose of the map. Nevertheless, substantial contribution to our understanding of the cartographic selection process is expected from the study of selection based on ordered (single-represented) objects.

3.2. The Principle of equal information density

The principle of constant information density can be derived from Töpfer's radix law [Meier, and Keller, 1991; Töpfer, and Pillewitzer, 1964]:

$$n_f = n_a * (m_a/m_f)^{n/2} \quad (1)$$

where m_a is the given scale,
 m_f the following scale,
 n_a the number of objects at the given scale,
 n_f the number of objects at the following scale, and
 n is the selection level.

Reformulating this law in terms of window area with $n=4$ and not in terms of the map scale, results in

number of objects / area = constant.

Retrieving a map at a given scale requires a top down search of the DAG. This search is guided by comparing spatial locations of the objects with the window of interest. Such comparisons are fast (linear in the number of objects compared), and the DAG can be structured such that only the relevant part must be searched.

The depth of the search in the relevant part of the DAG is bounded by the amount of graphical objects which can be shown. The test if an object can be shown is based on testing that the required space is free; a test requiring constant time per object. Most of the objects tested are also included in the output. Therefore the search process is linear in the number of objects included in the output, which is - following the principle of constant information density - constant.

3.3. The 'ink' notion

A *perfect method* to achieve uniform information density requires a method to measure the information an object contributes to the map. The algorithm would then descend the DAG, within the limits of the window, and refine objects till the desired level is achieved. Note the difference to a rank order selection: all objects within the window are selected initially, and the process is refining or expanding objects till the desired amount of detail is achieved (this requires that all objects are initially included in a highly generalized fashion, which is a zero rendering).

This method is idealized and methods to measure information content of a cartographic object are currently unknown. A simplistic application of information theory [Shannon,

1948] cannot deal with this particular case, where the information content of an individual object must be measured.

A practical method is to measure '*ink*', i.e. pixels which are black. One assumes that there is an optimal ratio of ink to paper. This ratio must be experimentally determined, measuring manually produced good maps (we expect a ratio of black pixels to total pixels). The expansion of the DAG is progressing from the top to the bottom, accumulating ink content and stopping when the preset value for graphical density is reached. The ink content would be measured not for the full window, but the window will be subdivided and ink for each subdivision optimized.

4. CONCLUSIONS AND FUTURE WORK

A number of applications requires graphical presentations of varying scale, from overview sketches to detailed drawings. The approach used here assumes that generalized versions of a map for an area are available and could be stored in a multi-scale DAG, where features which represent the same object, are linked. From such a multi-scale DAG, a map of arbitrary scale can be deduced by searching in the DAG till sufficient objects within the window of interest are found to produce a map of the same information density than the previous map. The principle of constant information density, which is number of objects/area = constant for the following scale, can be derived from Töpfer's radix law. We measure the information density with the practical method of counting '*ink*'. Retrieving a map at a given scale requires a top-down search of the DAG, accumulating the number of black pixels within a given area until a preset value is reached.

The concept is based on a trade-off between computation and storage, replacing all steps which are difficult to automate with storage. These difficult steps are performed initially, while the remaining steps, which can be easily automated, are performed each time a query asks for graphical output. All operations where valuable human time is necessary are done once only and the results are stored.

For each of the object groups in a map, a different DAG is necessary. It is subject to further studies how these different DAGs interact. We propose to define the structure formally, e.g. with algebraic specification, and study the interaction possibilities.

The resulting DAG structure is more complex, than spatial hierarchical structures proposed in the literature so far and methods to deal with dangling branches and subbranches have to be found.

Changes in the map correspond to operations in the DAG and these have impact on the structure of the DAG. Operations for zooming in and for generalizing are inverse but highly ambiguous. Further studies on this subject are necessary, before a DAG structure can be fully implemented.

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