A Theory of Change for Attributed Spatial Entities

John Stell[1] and Michael Worboys[2]

[1] School of Computing, University of Leeds, Leeds, LS2 9JT, UK
[2] Department of Spatial Information Science and Engineering, University of Maine, Orono, ME 04473, USA

Abstract. New methods of data collection, in particular the wide range of sensors and sensor networks that are being constructed, with the ability to collect real-time data streams, provide a driver for an appropriate underlying theory for information related to dynamic geographic phenomena. This paper investigates the underlying processes by which entities with both spatial and aspatial components may evolve and change through time, and how the spatial and aspatial dimensions participate separately and together in such an evolution. The overall structure that we propose is that of attributed locations in space-time. After motivation and a survey of relevant background work, the paper introduces a formal framework and presents a case study that applies it to a detailed example. The focus is the impact of spatial change on attribute change, but also considered is the converse process. We conclude by discussing the relevance of this work to the extraction of dynamic objects and their changes from sequences of temporal snapshots of static scenes.

1 Introduction

New methods of data collection, in particular the wide range of sensors and sensor networks that are being constructed, with the ability to collect real-time data streams, provide a driver for an appropriate underlying theory for information related to dynamic geographic phenomena. There has already been research, some of which is detailed in section 2, into the purely geometrical and topological aspects of such phenomena. This paper describes research that also brings into play some of the non-spatial aspects, sometimes called the attribute or semantic components of geographic information. We investigate the underlying processes by which entities with both spatial and aspatial components may evolve and change through time, and how the spatial and aspatial dimensions participate separately and together in such an evolution.

Components of a geospatial feature include not only spatial properties (e.g., location, shape, size) and relationships (Euclidean, metric and topological relations), but also attribute properties (e.g., level of a scalar value such as temperature). In a collection of features, objects may change in their spatial relationships with each other in addition to changes to themselves. Objects may come in to the scene, as well as leave it. The events themselves may be part of larger patterns, comprising of many “atomic events.” A sequence of snapshots is insufficient in itself, without further reasoning, to determine the underlying changes.

To take a very simple example, the left hand side of figure 1 shows two snapshots, A and B, of the evolution of a region. What cannot be determined is whether the change from A to B results in engulfment, as in the upper intermediate state, or creation of a hole, as in the lower. It is interesting that information about non-spatial properties of the entity (in this case, color), provides the possibility of more finely-tuned reasoning. Looking at the right-hand part of figure 1, if we assume that colors of individual regions cannot change, except by growth of new components, then the engulfment process can be eliminated from the evolution of the region from C to D. Although this is an artificial and simplified example, it shows the framework presented in this paper, namely analysis of the evolution of mixes of spatial and aspatial properties.

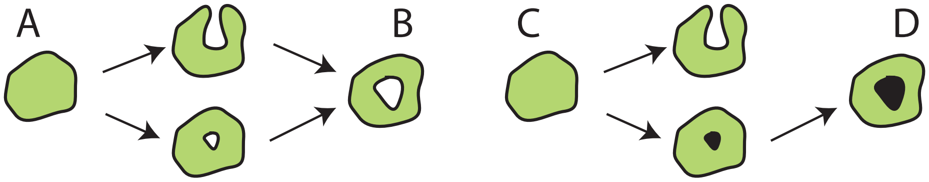

Fig. 1. Engulfment or hole growth?

Figure 2 shows a typical representation of spatial data, taken from a sample of the Ordnance Survey of Great Britain's MasterMap dataset. In it we see the spatial footprints of real world entities represented by polygons, while other attributes are indicated by text and color. When we look more closely at the representation we see a mix of data about particular entities, such as 'Manchester House' and the polygon that represents its spatial footprint, as well as more general information, such as 'PH', indicating that an entity whose spatial footprint is represented by a specific polygon is in the category of public houses, or the color blue indicating a road. Now, this representation is purely static, involving neither spatial nor aspatial change. If such changes are allowed, a range of questions arises, such as, 'How should a merge of the spatial footprint of one of the public houses merges with a neighboring house be represented?' 'What happens to the representation if Manchester House becomes a public house?'. Now the answer to any one of these questions might be straightforward, but reasoning about change requires a general foundation, and it is this foundation that is presented here.

The overall structure that we propose is that of attributed locations in space-time. The attributes may be natural-language, symbolic, or in any other appropriate form. In the case of the map in figure 2, the attributes are a mix of natural language, symbols, and colors. The choice of form of attribute is partly a question of representation, but more fundamental is the issue of the different ontological categories that the labels indicate. One dichotomy is between the *universal* and the *particular*. Universals have instances, are repeatable, abstract, and lack specific locations in space-time; while particulars have a unique spatio-temporal location. In figure 2, 'public house' is a universal while 'Manchester House' is a particular. Universals are commonly divided into *types*, *properties*, and *relations*. Types may be thought of as having instances that are 'objects', in some sense. Thus 'public house' is a type, whose instances are particular public houses at specific locations. An example of a property is 'rectangular', referring

Fig. 2. Typical representation of spatial data (Reproduced by permission of Ordnance Survey. (c) Crown Copyright)

to the shape of a land parcel, and an example of a relation is ‘adjacent’, indicating a relationship between two land parcels. We will see in what follows that it is important to know what category our attributes fall into, as well as the structure of the category, in order to perform a correct analysis.

This paper reports research on the interaction between instances and their types as they evolve. The evolution will often be considered to be through time. So, an example of a typical question is, when two patches of liquid attributed by distinct liquid types become merged, what is the type associated with the merged instance? But the framework also applies when the evolution is in representation, as for example when a spatial representation is generalized. For example, suppose that a land parcel attributed with type house is merged with a land parcel of type garden, what is the type of the merged parcel? Our framework will be seen to cover both these cases.

The structure of this paper is as follows. After this introduction is given a review of some relevant background work. We will then introduce the framework and present a case study that applies it to a detailed example. The next section considers related questions, especially the dual issue of the impact of a change of types upon the representation of the instances. The paper concludes with a summary and consideration of future directions.

2 Background

Research in the area of spatio-temporal information systems is now well-established. Early work includes a general survey of early work with a database orientation [1];

a description of a proposal for a temporal query language [9], and construction of a model of spatio-tempral information with a focus on region evolution [13]. An important event that established a research agenda for spatio-temporal reasoning in geographic spaces was the 1993 National Center for Geographic Information and Analysis Specialist Meeting [4].

Analysis of dynamic scenes, particularly as found in the computer vision community, has traditionally been quantitative and data-intensive (see, for example, [5]). General foundational work on types of object evolution, not specifically related to spatial change is reported by Hornsby and Egenhofer in [7]. The foundation for giving first-class status to events was set out ontologically by Grenon and Smith in [6] and from an information modeling and reasoning perspective by Worboys in [14]. Grenon and Smith extended the usual ontologies of things in snapshot (so-called SNAP ontologies) to include entities that are changes, occurrences, processes, and events (SPAN ontologies). Worboys analyzed changing spatial entities, including dynamic spatial phenomena from the SPAN perspective, and showed how techniques applied to computational processes, including process calculi and the event calculus used in artificial intelligence for robotic reasoning, could be applied in the geospatial context. The specifically spatial dimension of change has been analyzed in the context of basic topological change by Jiang and Worboys in [8]. This builds upon work on transitions between topological states, as found for example in [3], where a network structure is presented in which node represent topological relationships between two regions, and two nodes are direct neighbors if no sudden spatial “jump” is needed to get from one relationship to the other. Stell [11] considered how evolving entities could be described at different levels of detail through a granular account of time.

Some of the inspiration for the formal structures developed later in the chapter comes from work on Chu categories as developed in theories of information transfer between components of distributed systems. A good reference for this work is [2] on information flow and [12] on the more formal properties of Chu spaces.

There are many applications of spatial change reported in the literature, from the engulfment of cytoplasm by bacteria, to patterns of evolution of a gene sequence, to land type and use change. Research on evolutionary biology has also inspired some of the idea in this proposal, in particular work by theoretical biologists on topological spaces in patterns of evolutionary change (see, for example, [10]).

3 Formal framework

In this section we set out the formal properties that we expect the operation of combination to possess. We then outline the basic formal structure, around which this work is based, and show how it applies to a simple example. Assume that we have a set of spatial objects (e.g., regions, or links on a network), each of which has some attribution. For example, a region of land might have a land type associated with it. We make the simplifying assumption that each object has one and only one attribute (although of course, such an attribute might be a vector of simpler types). So, let X be a set of spatial objects and T be a set of attributes (called here *types*).

We assume that the spatial objects may change and combine in terms of their spatial extents. Thus, an object might move, rotate, dilate, grow a hole, merge with another, split, engulf another, and so on. We will focus specifically on the types of movement involving changes in the topology of the total assemblage. Merging, splitting, insertion, and deletion provide the principal topological changes to the spatial extents under consideration here. The investigation of these topological changes on their own, with no attributes, is the subject of earlier research [8]. Their possible influence on attribute changes is shown by an example in figure 3. Here we see the evolution of a pair of areal objects, attributed in this case by colors. The top object merges with itself, forming a hole, while the lower one splits. One piece of the lower object migrates and merges with the upper object, while the other develops a hole. In the case of colored liquids, we can imagine the effect to be as shown.

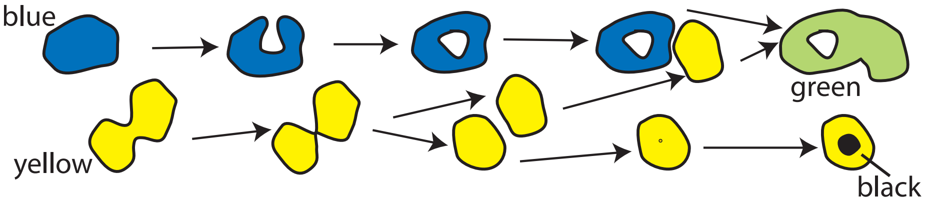

Fig. 3. Splitting and merging attributed spatial objects

3.1 Combining entities

The focus of this work is the effect of topological change on the attribution of areal objects. To begin to understand this, we must consider the structure of the domain from which the attributes are taken, and the effect of this structure on combination, splitting, and recombination. It is clear that a combination of colors, that might occur in the mixing of paints, is rather different from a combination of land use types that might take place in the generalization of a spatial representation. There are other cases, such as the combination of a husband and wife into a married couple that introduce further complexities. To indicate the differences, we might reasonably say that a husband is part of a married couple, and but maybe less obvious that the color blue is a part of the color green or that the type house is part of the type residence. In the first case, the structure of the domain is mereological, while in the second and third examples, we have a subsumption structure.

We now make some assumptions about the domains of interest, and the properties that mixing or combination has for those domains. Let T be the domain of attributes. For the set T, we impose a structure that models the ability for types to combine. Define a binary operation $\vee$ on T, where $a \vee b$ which is to be interpreted the type formed by the mix or combination of types a and b. We impose the following properties on the structure $\langle T, \vee \rangle$:

- For all $a, b, c \in T$, $(a \vee b) \vee c = a \vee (b \vee c)$. (Associativity)
- For all $a \in T$, $a \vee a = a$. (Idempotence)
- For all $a, b \in T$, $a \vee b = b \vee a$. (Symmetry)
- There is an element $\bot$, such that for all $a \in T$, $a \vee \bot = a$. (Existence of a bottom element)

These properties can be interpreted in a natural and intuitive way as properties of combination. Combination is assumed to be associative, and idempotence reflects the idea that mixing a quality with itself produces no change. We assume that the order of combination is not important (symmetry), and that there is a “zero” quality that when mixed with any quality leaves it unchanged. This is just one set of plausible properties, and the application would determine what formal properties would form the basis of an appropriate model. In the case above, $\langle T, \vee \rangle$ has the structure of a join semilattice with bottom element. As for the collection X of spatial objects, to begin with we give it no more structure than that of a set.

3.2 Combination of attributed objects

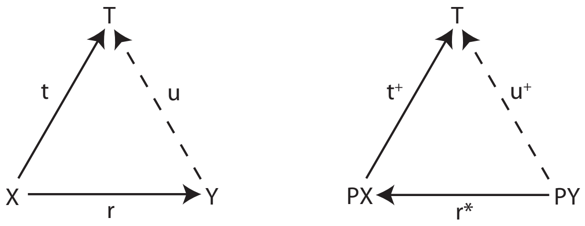

Fig. 4. Spatial object reformation

The first situation under discussion is represented by the arrow diagram shown in the left of figure 4. The objective is to find the effect on the typing of spatial objects if they are reformed. This shows a reformation of the spatial objects from the set X to the set Y, represented as a relation r from X to Y. So, for example, the merge of two objects x_1 and x_2 into object y is represented by $x_1 \, r \, y$ and $x_2 \, r \, y$, while the split of object x into objects y_1 and y_2 is represented by $x \, r \, y_1$ and $x \, r \, y_2$. The function t is a typing function, indicate the type tx of each element $x \in X$. We wish to construct typing function u, or at least to determine constraints upon its construction. So for example, we might expect that the type of the merged object y above reflects the types of its constituent objects, and that the types of the objects y_1 and y_2 are derived from the object from which they split. The exact rules will depend upon the application, so here is presented to outline of a general theory. We are assuming in this situation that the collection of types T is unchanged. This will be generalized later.

It is convenient to work wholly with functions rather than a mix of functions and a relation. To do this, we consider collections of objects, rather than the individual objects themselves. Hence, we construct functions $r^* : PY \to PX$ and $t^+ : PX \to T$ as follows.

$$r^* : B \mapsto \{x \in X \mid x\, r\, b \text{ for } b \in B\}, \text{ where } B \subseteq Y \tag{1}$$

$$t^+ : A \mapsto \bigvee_{s \in A} ts, \text{ where } A \subseteq X \tag{2}$$

It is not difficult to see that if we can find function $u^+ : PY \to T$, it is then possible to reconstruct function u by the rule that $uy = u^+\{y\}$. All that remains is to state the rule for constructing function u^+, (alternatively, the constraint on u^+). This is given by equation 3.

$$u^+ = t^+ r^* \tag{3}$$

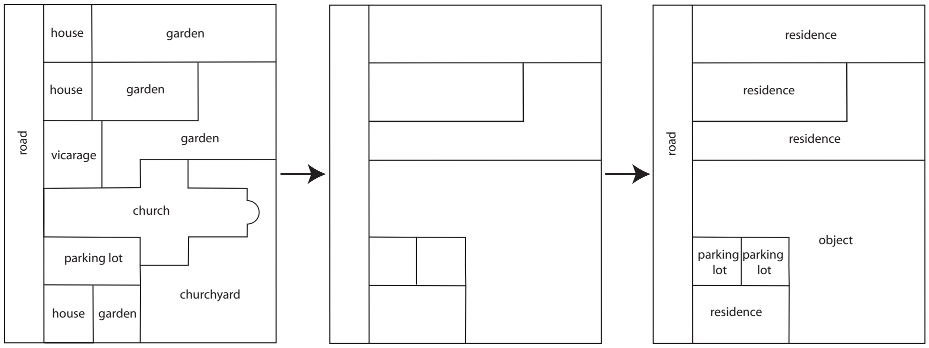

Fig. 5. Spatial scene reformation

3.3 Example: Spatial representation generalization

Let us work through this formalism by means of an example. The left hand portion of figure 5 shows a configuration of spatial objects. This configuration can be represented as a pairing of a set of instances $X = \{\mathsf{a}, \mathsf{b}, \mathsf{c}, \mathsf{d}, \mathsf{e}, \mathsf{f}, \mathsf{g}, \mathsf{h}, \mathsf{i}, \mathsf{j}, \mathsf{k}, \mathsf{l}\}$ with a set of types T. The types have the additional structure of a join semilattice, and are shown in figure 6. The explicit pairings are shown in figure 7, where in this case each instance in X is related to a unique type in T through its spatial situation as an areal object. Because the relationship between instances and spatial situations is a 1-1 correspondence, the pairing t between instances and types is functional. So, for example $t : \mathsf{a} \mapsto \mathsf{house}$.

Now, imagine that a map reformation operation entails the merging and splitting of areal objects, as shown in the middle portion of figure 5. This reformation entails a relation r from instances to merged/split instances, as shown in figure 8. For example, the regions attributed a and b have been merged into the region attributed a', and the region attributed i has been split into the regions attributed f' and g'. Relation r is fully specified by, $\mathsf{a} r \mathsf{a}'$, $\mathsf{b} r \mathsf{a}'$, $\mathsf{c} r \mathsf{b}'$, $\mathsf{d} r \mathsf{b}'$, $\mathsf{e} r \mathsf{c}'$, $\mathsf{f} r \mathsf{c}'$, $\mathsf{g} r \mathsf{d}'$, $\mathsf{h} r \mathsf{e}'$, $\mathsf{i} r \mathsf{f}'$, $\mathsf{i} r \mathsf{g}'$, $\mathsf{j} r \mathsf{e}'$, $\mathsf{k} r \mathsf{h}'$, and $\mathsf{l} r \mathsf{h}'$.

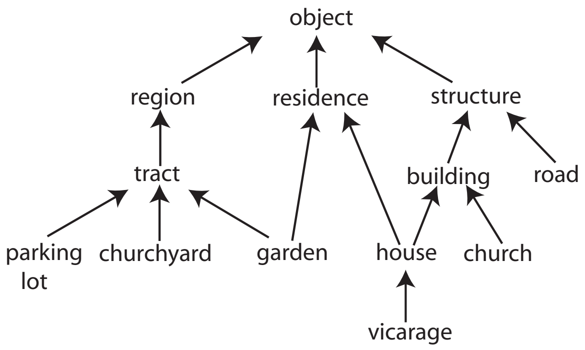

Fig. 6. Land typology

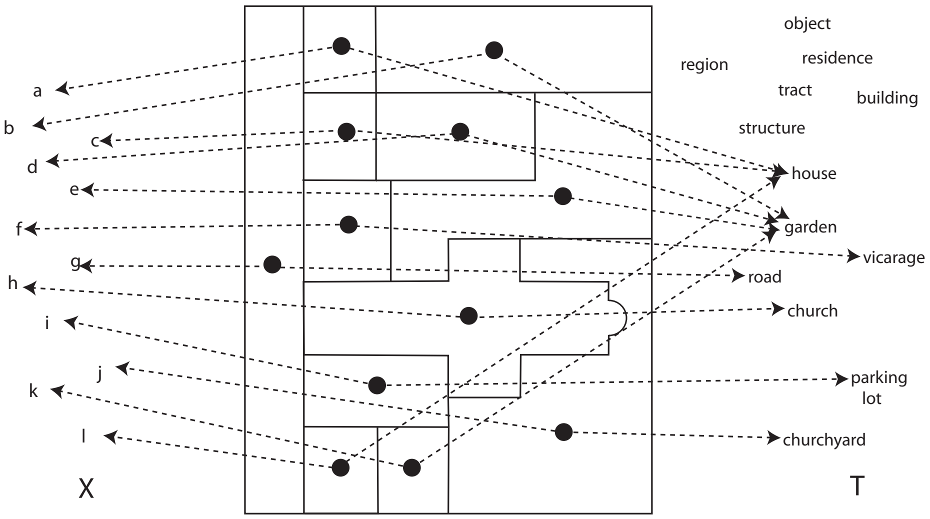

Fig. 7. Links between objects and types

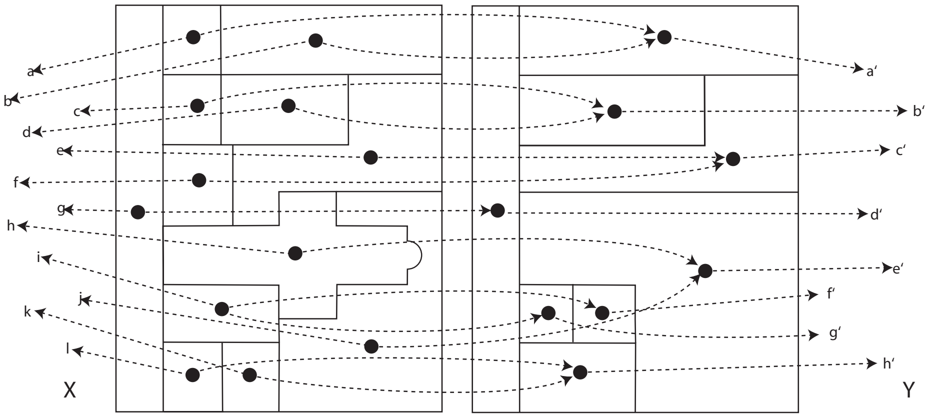

Fig. 8. Links between objects and their splits and merges

The function r^* defined by equation 1 can now be constructed. Firstly, construct the action of r^* on singleton sets, with, for example:

$$\begin{aligned} r^* &: \{\mathsf{a}'\} \mapsto \{\mathsf{a}, \mathsf{b}\} \\ r^* &: \{\mathsf{b}'\} \mapsto \{\mathsf{c}, \mathsf{d}\} \\ r^* &: \{\mathsf{f}'\} \mapsto \{\mathsf{i}\} \\ r^* &: \{\mathsf{g}'\} \mapsto \{\mathsf{i}\} \end{aligned}$$

Then, the action of r^* on non-singleton subsets is computed by taking the union of its actions on the singleton constituents. So, for example:

$$r^* : \{\mathsf{a}', \mathsf{b}'\} \mapsto \{\mathsf{a}, \mathsf{b}\} \cup \{\mathsf{c}, \mathsf{d}\} = \{\mathsf{a}, \mathsf{b}, \mathsf{c}, \mathsf{d}\}$$

In a similar way, function t^+ defined by equation 2 is constructed by computing its action on singleton sets, with, for example:

$$\begin{aligned} t^+ &: \{\mathsf{a}\} \mapsto \textsf{house} \\ t^+ &: \{\mathsf{b}\} \mapsto \textsf{garden} \\ t^+ &: \{\mathsf{i}\} \mapsto \textsf{parking lot} \end{aligned}$$

Then, the action of t^+ on non-singleton subsets is computed by taking the join of its actions on the singleton constituents. So, for example:

$$r^* : \{\mathsf{a}, \mathsf{b}\} \mapsto \textsf{house} \vee \textsf{garden} = \textsf{residence}$$

The final step is to construct function u^+, as defined by equation 3, as the composition of t^+ with r^*. So, for example:

$$u^+ : \{\mathsf{a}'\} \mapsto \{\mathsf{a}, \mathsf{b}\} \mapsto \textsf{residence}$$
$$u^+ : \{\mathsf{f}'\} \mapsto \{\mathsf{i}\} \mapsto \textsf{parking lot}$$
$$u^+ : \{\mathsf{g}'\} \mapsto \{\mathsf{i}\} \mapsto \textsf{parking lot}$$

This enables us to complete the attributes for each land area, as shown in the right-hand panel of figure 5. The example computations above are shown for the cases of a merge and a split, and in both cases lead to the result we would expect.

4 Further investigations

The preceding section set out the underlying structure, and showed how reformation of the scene of spatial objects implies a reconfiguration of types. In this section we look at one extension of this idea, where the types may also evolve, and then consider the converse case where a change of types will effect a reformation of the spatial scene.

4.1 Evolution of the type structure

In this section, we not only allow the spatial objects to change, but also the types. Changes to the type domain correspond in database terminology to *schema evolution*. This more general framework is shown in figure 9. There are two type domains, T and U, and a function s between them. In some cases, it might be appropriate to constrain s to be a function that preserves the structure of the type domains, so in our paper s would be a join-semilattice morphism. For example in the case of spatial representation generalization, it might well be appropriate to assume that the type domain for the generalized map is a homomorphic image of the source type domain. However, this is not essential in what follows.

The extension is quite straightforward. The equations 1 and 2 are as before, but equation 3 is modified to:

$$u^+ = s\,t^+ r^* \tag{4}$$

4.2 Effect of type changes upon the underlying spatial representation

Next, we investigate the degree to which merging attributes has an impact on the spatial representation. In maps, we can observe that a common annotation between neighboring regions might allow cross-border integration. Returning to the example of section 3.3, suppose that we assume some combination of types, and wish to infer a reformation of the spatial representation. For concreteness, assume we have the following mapping $s : T \to U$, given by s : house $\mapsto$ residence, s : garden $\mapsto$ residence, s : vicarage $\mapsto$ residence, and s acts as the identity on all other members of T. (Note by the way that $s : T \to U$ is a join-semilattice morphism.) If we followed through a process dual to that in section 3.3, we would like to be able to conclude that a pair of spatial regions that are attributed house and garden in T have the possibility of merging into a single region

$$\begin{tikzcd}
T \arrow[r, "s"] & U \\
PX \arrow[u, "t^+"] & PY \arrow[l, "r^*"] \arrow[u, "u^+"']
\end{tikzcd}$$

Fig. 9. Generalized reconfiguration arrow diagram

attributed by residence in U. Of course, we do not want all such pairs of objects to be merged. Firstly, they must be share a common boundary, and even that is insufficient (note regions attributed f and d in figure 8. We need more information to correctly merge the appropriate regions. This points to a basic lack of duality between spatial objects and their types.

5 Conclusions

In this paper, we have argued that static representations of the beginning and ending of a change are insufficient in general to determine the nature of the change. The change needs itself to be explicitly represented. To this end, we developed earlier work on the explicit and formal representation of purely spatio-topological change so that changes of attributed spatial objects may be also represented. The formalism was applied to an example where changes take place to a representation through the process of generalization. A key issue was the effect that the structure of the spatial and attribute domains had upon the overall structure, and we examined the particular case where the attribute domain had the structure of a join-semilattice under attribute combination. In the first stage of the work, only the spatial domain was allowed to evolve through change, but in the second we extended the formalism to allow both spatial structure and attribute domain evolution.

One of the as yet only partially solved problems in spatio-temporal reasoning is the extraction from a temporal sequence of spatial snapshots a collection of dynamic and evolving spatial objects. We expect the formalism developed here to allow the construction of constraints imposed by pairs of spatial snapshots to possible object evolutions within the sequence. Figure 10 shows an example of the process carried through five time steps, t_1 up to t_5. The top portion of the figure shows the dynamic spatial scene, comprising of a temporal sequence of scene snapshots. The approach is to utilize the formal constraints, as developed above, to identify possible relationships between the objects in consecutive snapshots. These relationships will be labeled with uncertainty

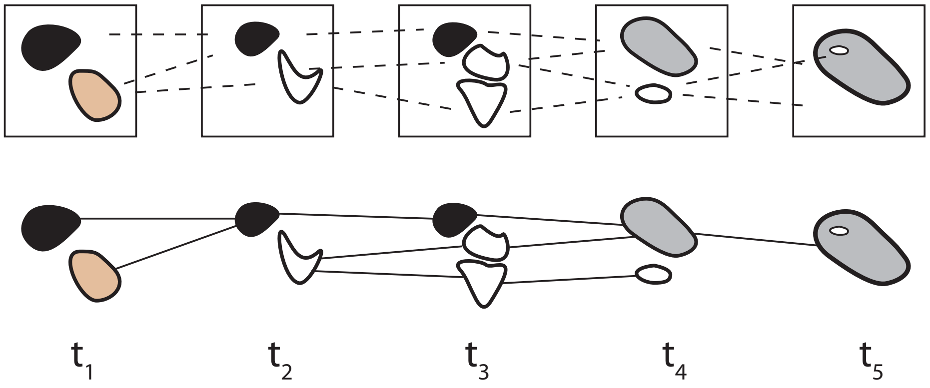

Fig. 10. Extracting dynamic objects from sequences of scene snapshots

levels, according to weight of evidence that a relationship exists. In the lower half of the figure, the weighted relationships have been used to determine the dynamic object and its change relationships. In the example, there are merge, creation, splitting, attribute change, attribute combination, destruction, and hole formation change events. This is the subject of ongoing work.

6 Acknowledgments

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