An Architecture for Semantic Analysis in Geospatial Dynamics

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Abstract. We present the conceptual and operational overview and architecture of a framework for semantic – high-level, qualitative – reasoning about dynamic geospatial phenomena. The framework is based on advances in the areas of geospatial semantics, qualitative spatio-temporal representation and reasoning, and reasoning about actions and change. We present the main operational modules, namely the modules for data qualification and consistency, qualitative spatial data integration and conflict resolution, and high-level explanatory analysis.

Keywords: geographic information systems; spatio-temporal dynamics; events and objects in GIS; geospatial analysis

1 Introduction

Geographic information systems (GIS) and geospatial web applications are confronted with massive quantities of micro and macro-level spatio-temporal data consisting of precise measurements pertaining to environmental features, aerial imagery, and more recently, sensor network databases that store real-time information about natural and artificial processes and phenomena. In many applications multiple such data sets need to be combined on the fly in order to provide an adequate basis for high-level spatio-temporal analysis. Within next-generation GIS systems, the fundamental information theoretic modalities are envisioned to undergo radical transformations: high-level ontological entities such as *objects*, *events*, *actions* and *processes* and the capability to model and reason about these are expected to be a native feature of next-generation GIS [27]. Indeed, one of the crucial developmental goals in GIS systems of the future is a fundamental paradigmatic shift in the underlying '*spatial informatics*' of these systems.

The spatial information theoretic challenges underlying the development of high-level analytical capability in dynamic GIS consist of fundamental representational and computational problems pertaining to: the semantics of spatial occurrences, practical abduction in GIS, problems of data qualification and consistency, and spatial data integration and conflict resolution. Research in the area of geospatial semantics, taxonomies of geospatial events and processes, and basic ontological research into the nature of processes in a specific geospatial context has garnered specific interest from several quarters [3, 9, 19, 21, 22, 23, 30, 33]. Research has mainly been spurred by the realization that purely snapshot-based temporal GIS do not provide for an adequate basis for analyzing spatial events and processes and performing spatio-temporal reasoning. Event-based and object-level reasoning at the spatial level can serve as a basis of explanatory analyses within a GIS [13, 18, 26, 32]. Advances in formal methods in the areas of qualitative spatio-temporal representation and reasoning [11], reasoning about actions and change, and spatio-temporal dynamics [4, 8] provide interesting new perspectives for the development of the foundational spatial informatics underlying next-generation GIS systems.

Building on these existing foundations from the GIS and AI communities, we propose an overarching formal framework, and its corresponding conceptual architecture, for high-level qualitative modeling and analysis for the domain of geospatial dynamics. The input is assumed to consist of data sets from several data sources and the framework encompasses modules for different aspects such as *qualification*, *spatial consistency*, *data merging and integration*, and *explanatory reasoning* within a logical setting.

We give a brief overview of the proposed architecture in the next section and then describe and discuss the different components in detail in the following sections. In doing so, we address basic representational and computational challenges within the formal theory of space, events, actions and change.

2 Geospatial Analytics: A Formal Framework

In the following, we propose and explain a formal framework and its corresponding conceptual architecture for high-level qualitative modeling and (explanatory) analysis for the domain of geospatial dynamics.

Fig. 1 illustrates the architecture with its different modules, which we explain in detail in Sections (3–5). The main aspects of the proposed architecture are the following: The input consists of data sets from several data sources such as remote sensing, spatial databases, sensors etc. These data sets are then processed to derive qualitative spatial observations associated with specific time points to be handed over to the actual analytical reasoning component. This preprocessing is done by a module responsible for partitioning the input data into time points and merging data associated with the same time point including the resolution of spatial conflicts between the different data sources and wrt. given spatial integrity constraints. This module is supported by other modules for performing qualification and spatial consistency checking. The pre-processed temporally-ordered observations constitute configurational and narrative descriptions and serve as the input to the reasoning component, which embeds in the capability to perform explanatory reasoning. The knowledge derived by the reasoning component for a particular domain under consideration can be utilized by ex-

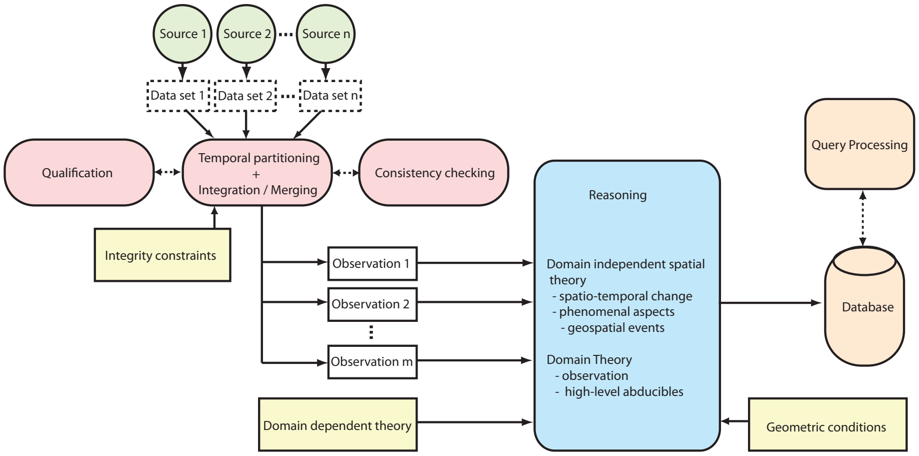

Fig. 1: Conceptual architecture for high-level modeling and explanatory analysis.

ternal services (e.g., query-based services) and application systems that directly interface with humans (e.g., experts, decision-makers).

3 Qualification and Spatial Consistency

Logical frameworks for performing explanation with spatial information generally require that the input information is consistent, meaning that the combined input data is compliant with the underlying logical spatial theory. However, in the geographic domain, the input data often stems from multiple sources, for instance from different sensors, remote sensing data, map data, etc., and the data itself is afflicted by measurement errors and uncertainty. Hence, the geo-referenced quantitative input data about spatial objects needs to be preprocessed in order to be used to perform explanation on a level of qualitative spatial relations. This preprocessing involves the temporal partitioning of the input data into an ordered sequence of time points and the formulation of consistent qualitative descriptions called *observations* for each time point. Crucial sub-components involved in the generation of these descriptions are modules for translating geo-referenced quantitative data into relations from several qualitative spatial models dealing with different aspects of space, a process referred to as *qualification*, and for checking the consistency of the combined information. Both modules are utilized by the main preprocessing module responsible for qualitative integration including the resolution of contradictions as explained further in the next section.

The qualification procedure needs to consider all data that concerns the same moment in time and compute relations for all n-tuples of objects where n corresponds to the arity of the relations in the given qualitative model (e.g., binary topological relations such as *contained* or *disjoint*, or cardinal directions rela-

(a) (b) (c) (d)

Fig. 2: Information from four different sources which is inconsistent when combined.

tions such as *north-of*). If uncertainty of quantitative information is explicitly represented this needs to be taken into account and may lead to disjunctions on the qualitative level.

Due to the mentioned measurement errors and uncertainty of the quantitative input data, the qualitative descriptions resulting from qualification for particular moments in time may contain contradictions or violate integrity constraints stemming from background knowledge about the application domain. Fig. 2 illustrates the case of a spatial inconsistency on the level of topological relations when combining the information from four different sources (all concerning the same time period): From combining the fact that objects c and d (e.g., two climate phenomena) are reported to *overlap* by one source (a) with the reported relations c is completely *contained in* a (b) and d is completely *contained in* b (c) (let us say a and b are two neighbored states) it follows that the two states a and b would need to overlap as well. This contradicts the information from the fourth source (d) which could for instance be a spatial databases containing state boundaries (or alternatively be given in the form of a general integrity constraint).

As a result of the possibility of inconsistent input information occurring in geographic applications, frameworks for explanation and spatio-temporal analysis need the ability to at least detect these inconsistencies in order to exclude the contradicting information or, as a more appropriate approach, resolve the contradictions in a suitable way. Deciding consistency of a set of qualitative spatial relations has been studied as one of the fundamental reasoning tasks in qualitative spatial representation and reasoning [11]. The complexity of deciding consistency varies significantly over the different existing qualitative calculi. For most common qualitative calculi such as the Region Connection Calculus (RCC-8) [29], the consistency can be decided in cubic time when the input description is a scenario which means it does not contain disjunction. This is achieved by the path consistency or algebraic closure method [24]. For general descriptions including disjunctions a more costly backtracking search has to be performed.

Integrity constraints have been investigated in the (spatial) database literature [10, 16]. As the example above shows, in a geographic context, integrity rules often come in the form of qualitative spatial relations that have to be satisfied by certain types of spatial entities. These kinds of spatial integrity constraints can be dealt with by employing terminological reasoning to determine whether a certain integrity rule has to be applied to a given tuple of objects and feeding the resulting constraints into a standard qualitative consistency checker together with the qualitative relations coming from the input data.

4 Spatial Data Integration and Conflict Resolution

When conflicts arise during the integration of spatial data, it is desirable to not only detect the inconsistencies but also resolve conflicts in a reasonable manner to still be able to exploit all provided information in the actual logical reasoning approach for explanation and analysis. Methods for data integration and conflict resolution have for instance been studied under the term information fusion [20]. Symbolic information fusion is concerned with the revision of logical theories under the presence of new evidence. Different information fusion settings have led to the formulation of different rationality criteria that corresponding computational approaches should satisfy such as the AGM postulates for belief change [1]. Such computational solutions often consist of merging operators that compute a consistent model that is most similar to the inconsistent input data. In distance-based merging approaches this notion of similarity is described using a distance measure between models. This idea has been applied to qualitative spatial representations [12, 14] using the notion of conceptual neighborhood [15, 17] to measure distance in terms of the number of neighborhood changes that need to be performed to get from inconsistent qualitative descriptions to consistent ones.

Fig. 3 shows an example from the domain of urban dynamics that illustrates the role of integration with conflict resolution as well as qualification and consistency checking. Let us assume that we have spatial data from different sources: Source 1 provides information about different land use zones including parks, residential zones, industrial zones, which are derived analyzing aerial images. Source 2 provides information about natural reservoirs, that is about parks and mangroves, stemming from a spatial database. Let us furthermore assume that the land use types are defined in a mutually exclusive way such that two different zones cannot overlap. We now follow the procedure for integrating this information sketched in Alg. 1 that takes a set of observations $\mathcal{O}$, one for each source, containing object identifiers with associated geometries and a set $\mathcal{IC}$ of integrity constraints. Fig. 3(a) illustrates part of the combined information from all sources for a particular time point t. Source 1 and source 2 both contain geo-referenced polygons for a park but this information does not match. The first step now is to qualify the geometric data from source 1 and 2 which results in the qualitative constraint network Q.[3] Using RCC-8 this network looks as shown in Fig. 3(b) (p and p' represent the different geometries for the same park object). If network Q is consistent and compliant with the integrity constraints, the result can directly be handed over as an observation to the reasoning module. However, as also shown in Fig. 3(b) this is not the case as integrity constraints

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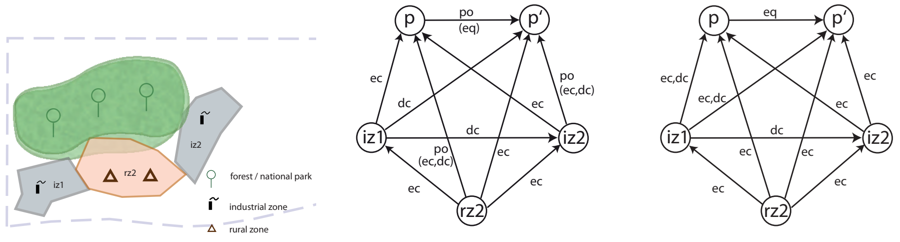
[3] Alternatively, information for each data set could be qualified separately resulting in several constraint networks that have to be combined by a suitable merging operator.



(a) (b) (c)

Fig. 3: Qualification of the combined geometric information (a) together with the integrity constraints results in an inconsistent qualitative model (b). The consistent model after resolving the conflicts (c).

are violated in three places indicated by listing possible relations following from the integrity constraint in brackets below the original relation. The relation between p and p' should be eq simply because it is known that both represent the same object. The relation between rz_2 and p should be either ec or dc because of our integrity constraint, and the same holds for the relation between p' and iz_2. Therefore, the qualitative conflict resolution component needs to be called to find a qualitative representation that is as close as possible to the network from Fig. 3(b) but is overall consistent.

To achieve the conflict resolution, a resolution operator Λ based on the idea of distance-based merging operators for qualitative spatial representations [12, 14] is applied to Q. Our resolution operator Λ is based on a distance measure $d(s, s')$ between two scenarios over the same set of objects. It is computed by simply summing up the distance of two base relations in the conceptual neighborhood graph of the involved calculus given by $d_B(C_{ij}, C'_{ij})$ over all corresponding constraints C_{ij}, C'_{ij} in the input scenarios:

$$d(s, s') = \sum_{1 \leqslant i < j \leqslant m} d_B(C_{ij}, C'_{ij}) \tag{1}$$

The resolved network $\Lambda(Q)$ is then constructed by taking the union of those scenarios that are consistent, compliant with the integrity constraints and have a minimal distance to Q according to $d(s, s')$[4]:

$$\Lambda(Q) = \bigcup_{s \in S(Q)} s \tag{2}$$

with

$$S(Q) = \{ s \in [\![QCN]\!] \mid \forall s' \in [\![QCN]\!] : d(s', Q) \geqslant d(s, Q) \} \tag{3}$$

and $[\![QCN]\!]$ standing for the set of all scenarios that are consistent and compliant with the integrity constraints. Following the approach described in [14], $\Lambda(Q)$

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[4] Taking the union here means we build a new network by taking the union of all corresponding constraints.

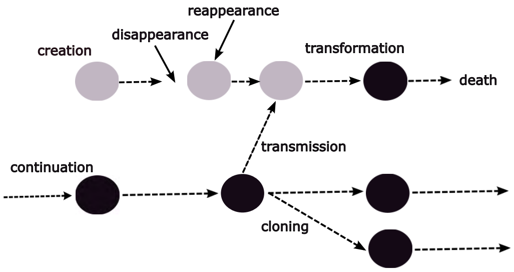

Fig. 4: Object Change History, Source: [32]

can be computed by incrementally relaxing the constraints until at least one consistent scenario has been found. This is illustrated in Alg. 2 where we assume that the function relax(Q,i) returns the set of scenarios s which have a distance $d(s', Q) = i$ to Q.

The result of applying the resolution operator to the network from Fig. 3(b) is shown in Fig. 3(c): Both violations of integrity constraints have been resolved by assuming that instead of 'overlap' the correct relation is 'externally connected'. Interestingly, the resulting consistent qualitatively model contains two disjunctions basically saying that the relation between the park and iz_1 is either ec or dc. This is a consequence of the fact that both qualitative models are equally close to the input model such that it is not possible to decide between the two hypotheses.

Algorithm 1: Qualify+Merge($\mathcal{O}, \mathcal{IC}$)

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$Q \leftarrow$ qualify($\mathcal{O}$)
if $\neg$consistent($Q, \mathcal{IC}$) then
    $Q \leftarrow \Lambda(Q, \mathcal{IC})$
end if
return $Q$
```

Algorithm 2: $\Lambda(Q, \mathcal{IC})$

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$i \leftarrow 0$, $N \leftarrow \varnothing$
while $N = \varnothing$ do
    $R \leftarrow$ relax($Q, i$)
    for $r \in R$ do
        if consistent($r, \mathcal{IC}$) then $N \leftarrow N \cup r$
        end if
    end for
    $i \leftarrow i + 1$
end while
return $N$
```

5 Analyses with Events and Objects

Our objective for the high-level reasoning module is to provide the functionality to enable reasoning about spatio-temporal narratives consisting of events and processes at the geographic scale. We do not attempt an elaborate ontological characterization of events and processes, a topic of research that has been addressed in-depth in the state-of-the-art (see Section 1). For the purposes of this paper, we utilize a minimal, yet rich, conceptual model consisting of a range of events such that it may be used to qualitatively ground metric geospatial datasets consisting of spatial and temporal footprints of human and natural phenomena at the geographic scale.

From an ontological viewpoint, spatial occurrences may be defined at two levels: (O1) *domain-independent*, and (O2) *domain-dependent*:

O1. Domain Independent Spatial Occurrences These occurrences are those that may be semantically characterized within a general theory of space and spatial change. These may be grounded with respect to either a qualitative theory, or an elaborate typology of geospatial events. Distinctions as per (A–B) are identifiable:

A. Spatial Changes at a Qualitative Level

In so far as a general qualitative theory of spatial change is concerned, there is only one type of occurrence, viz - a transition from one qualitative state (relation) to another as (possibly) governed by the continuity constraints of the relation space. At this level, the only identifiable notion of an occurrence is that of a qualitative spatial transition that the primitive objects in the theory undergo. At the level of a spatial theory, it is meaningless to ascribe a certain spatial transition as being an event or action; such distinctions demand a slightly higher level of abstraction. For example, the transition of an object (o_1) from being *disconnected* to another object (o_2) to being a $tangential-part$ of it could either coarsely represent the volitional movement of a person into a room or the motion of a ball. Whereas the former is an action performed by an agent, the latter is a deterministic event that will necessarily occur in normal circumstances. Our standpoint here is that such distinctions can only be made in a domain specific manner; as such, the classification of occurrences into actions and events will only apply at the level of the domain with the general spatial theory dealing only with one type of occurrence, namely primitive spatial transitions that are definable in it.

B. Typology of Events and Patterns

At the domain independent level, the explanation may encompass behaviours such as *emergence*, *growth* & *shrinkage*, *disappearance*, *spread*, *stability* etc, in addition to the sequential/parallel composition of the behavioural primitives aforementioned, e.g., *emergence* followed by *growth*, *spread / movement*, *stability* and *disappearance* during a time-interval. Certain kinds of typological elements, e.g., *growth* and *shrinkage*, may even be directly associated with spatial changes at the qualitative level in (A).

Appearance of new objects and disappearance of existing ones, either abruptly or explicitly formulated in the domain theory, is also characteristic of non-trivial dynamic (geo)spatial systems. Within event-based GIS, appearance and disappearance events are regarded to be an important typological element for the modeling of dynamic geospatial processes [9, 32]. For instance, Claramunt and Thériault [9] identify the basic processes used to define a set of low-order spatio-temporal events which, among other things, include appearance and disappearance events as fundamental. Similarly, toward event-based models of dynamic geographic phenomena, Worboys [32] suggests the use of the appearance and disappearance events at least in so far as single object behaviours are concerned (see Fig. 4). Appearance, disappearance and re-appearances are also connected to the issue of object identity maintenance in GIS [3, 22].

O2. Domain-Specific Spatial Occurrences At a domain-dependent level, behaviour patterns may characterize high-level processes, environmental / natural and human activities such as *deforestation, urbanization*, *land-use transformations* etc. These are domain-specific occurrences that induce a transformation on the underlying spatial structures being modeled. Basically, these are domain specific events or actions that have (explicitly) identifiable occurrence criteria and effects that can be defined in terms of qualitative spatial changes, and the fundamental typology of spatial changes. For instance, in the example in Fig. 5, we can clearly see that region a has continued to *shrink* over a three-decade period, followed by a *split*, and eventually *disappearing* in the year 1990.

The following general notion of a '*spatial occurrence*' is identifiable [6]:

> '*Spatial occurrences are events or actions with explicitly specifiable occurrence criteria and/or pre-conditions respectively and effects that may be identified in terms of a domain independent taxonomy of spatial change that is native to a general qualitative spatial theory*'.

As an example, consider an event that will *cause* a region to *split* or make it *grow / shrink*. Likewise, an aggregate cluster of geospatial entities (e.g., in wildlife biology domain) may *move* and change its orientation with respect to other geospatial entities. Thinking in agent terms, a spatial action by the *collective / aggregate* entity, e.g., *turn south-east*, will have the effect of changing the orientation of the cluster in relation to other entities. In certain situations, there may not be a clearly identifiable set of domain-specific occurrences with explicitly known occurrence criteria or effects that are definable in terms of a typology of spatial change, e.g., cluster of alcohol-related crime abruptly appearing and disappearing at a certain time. However, even in such situations, an analysis of the domain-independent events and inter-event relationships may lead to an understanding of spatio-temporal relationships and help with practical hypothesis generation [2].

Explanatory Reasoning in GIS: A Case for Practical Abduction

Explanatory reasoning requires the ability to perform abduction with spatio-temporal information. In the context of formal spatio-temporal calculi, and logics of action and change, this translates to the ability to provide *scenario and narrative completion* abilities at a high-level of abstraction.

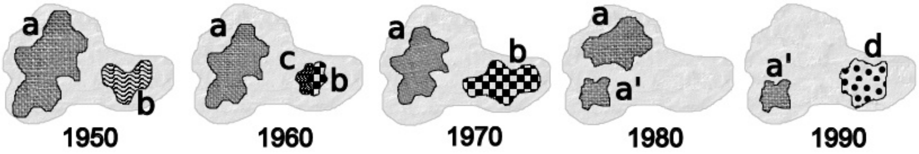

Fig. 5: Abduction in GIS

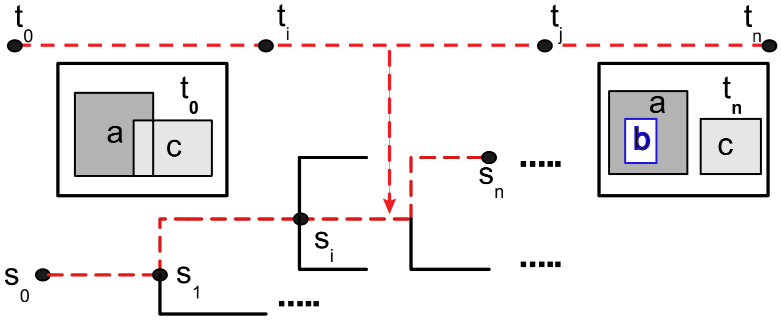

Fig. 6: Branching / Hypothetical Situation Space. Source [4]

Consider the GIS domain depicted in Fig. 5, and the basic conceptual understanding of spatial occurrences described in (O1–O2; Section 5). At a domain-independent level, the scene may be described using topological and qualitative size relationships. Consequently, the only changes that are identifiable at the level of the spatial theory are *shrinkage*, *splitting*, and eventual *disappearance* – this is because a domain-independent spatial theory may only include a generic typology (*appearance, disappearance, growth, shrinkage, deformation, splitting, merging* etc) of spatial change. However, at a domain-specific level, these changes could characterize a specific event (or process) such as *deforestation*. The hypotheses or explanations that are generated during a explanation process should necessarily consist of the domain-level occurrences in addition to the underlying (associated) spatial changes (as per the generic typology) that are identifiable. Intuitively, the derived explanations more or less take the form of existential statements such as: "Between time-points t_i and t_i, the process of deforestation is abducible as one potential hypothesis". Derived hypotheses / explanations that involve both domain-dependent and as well their corresponding domain-independent typological elements are referred to as being '*adequate*' from the viewpoint of explanatory analysis for a domain. At both the domain-independent as well as dependent levels, abduction requires the fundamental capability to interpolate missing information, and understand partially available narratives that describe the execution of high-level real or abstract processes. In the following, we present an intuitive overview of the scenario and narrative completion process.

Scenario and Narrative Completion Explanation, in general, is regarded as a converse operation to temporal projection essentially involving reasoning from effects to causes, i.e., reasoning about the past [31]. Logical abduction is one inference pattern that can be used to realize explanation in the spatio-temporal domain [5, 6].

Explanation problems demand the inclusion of a narrative description, which is essentially a distinguished course of actual events about which we may have incomplete information [25, 28]. Narrative descriptions are typically available as *observations* from the real / imagined execution of a system or process. Since narratives inherently pertain to actual observations, i.e., they are *temporalized*, the objective is often to assimilate / explain them with respect to an underlying process model and an approach to derive explanations.

Given the set of observations resulting from the preprocessing which constitutes a partial narrative of the evolution of a system in terms of high-level spatio-temporal data, scenario and narrative completion corresponds to the ability to derive completions that bridge the narrative by interpolating the missing spatial and action / event information in a manner that is consistent with domain-specific and domain-independent rules / dynamics. Consider the illustration in Fig. 6 for a branching / hypothetical situation space that characterizes the complete evolution of a system [5]. In Fig. 6 – the situation-based history $< s_0,\ s_1, \ldots,\ s_n >$ represents one path, corresponding to an actual time-line $< t_0,\ t_1, \ldots,\ t_n >$, within the overall branching-tree structured situation space. Given incomplete narrative descriptions, e.g., corresponding to only some ordered time-points in terms of high-level spatial (e.g., topological, orientation) and occurrence information, the objective of causal explanation is to derive one or more paths from the branching situation space, that could best-fit the available narrative information [6]. Of course, the completions that bridge the narrative by interpolating the missing spatial and action/event information have to be consistent with domain-specific and domain-independent rules/dynamics.

6 Conclusion

In our research, we are addressing a broad question: what constitutes the (core) spatial informatics underlying (specific kinds) of analytical capabilities within a range of dynamic geospatial domains [7]. In continuation with the overarching agenda described in [7], this paper has demonstrated the fundamental challenges and presented solutions thereof encompassing aspects such as *spatial consistency*, *data merging and integration*, and *practical geospatial abduction* within a logical setting. Whereas independently implemented modules for these respective components have been developed in our projects at the Spatial Cognition Research Center, the main thrust of our ongoing work in the current context is to fully implement the integrated framework / architecture described in this paper.

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