Identifying Geographical Processes from Time-stamped Data

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Abstract. Humans tend to interpret a temporal series of geographical spatial data in terms of *geographical processes*. They also often ascribe certain properties to processes (e.g. a process may be said to *accelerate*). Given a spatial region of observation, distinct properties may be observed in different subregions and at different times, which causes difficulties for humans to identify them. The conceptualisation of geographical features and their correlation with geographical phenomena may provide a human like approach to analyse large spatio-temporal datasets. This paper presents a representational model and a reasoning mechanism to analyse evolving geographical features and their relationship to geographical processes. The proposed approach comprises methods of relating occurrences of geographical events to geographical processes which is said to proceeds over time. We introduce an initial set of properties which can be associated with several geographical processes. We consider this as a first step towards a more general model for representing and reasoning about geographical processes.

Keywords: Spatial Reasoning, Temporal Reasoning, Ontology, Geographical Processes.

1 Introduction

Geographical features may change over time. These changes sometimes occur continuously, such as the clouds moving in the atmosphere, and sometimes happen in cycles, as for example the seasonal variation in vegetation. Some authors (e.g. [9, 11, 12]) have classified this type of changes as a *spatio-temporal processes*.

The features involved in such processes may undergo a variety of spatial transformations. For example, they can grow, shrink or move. When a spatio-temporal process comprises only changes of geographical features, we conceive it as a *geographical process*, whilst the features involved are taken as being the process' participants. Examples of geographical processes are *deforestation*, *urbanization* and *desertification*. The former, for instance, may be defined in terms of changes of the feature *forest*. In addition, these processes are generally associated with a set of *properties* which may be ascribed to them (for example, a process may be described as being *constant*, or *intermittent*, or *slowing down*, or *accelerating*). We introduce a set of properties which can be applied to a variety of geographical processes: *initiation* and *cessation*, *acceleration*, *deceleration* and *constant proceeding*. We also present an approach to identify if a process proceeds.

In this paper, we describe a representational model for those topographical and mereological changes in the geographical space, which we characterise as a geographical process. We also describe a reasoning mechanism to identify features whose changes are associated with properties of a geographical process. In order to evaluate our conceptual model, we have developed a system prototype which links an ontology to a spatio-temporal dataset. Thus, the prototype takes a temporal series of spatial data as an input and returns a set of features which matches a user query, which consists of the process' properties to be identified and spatial and temporal constraints.

Defining an appropriate representation for geographical processes requires dealing with issues regarding their relationship to events and objects. While the former may be conceived as constituents of processes [9], the latter may be regarded as *participants* in processes. In addition, objects are associated with a spatial extent at any one time and persist through changes in their attributes [8]. Other important issues are how to define the relation between process types and particular process instances, and how to associate specific spatial and temporal boundaries with process instances. Accordingly, our semantic model comprises methods of defining types and instances and provide an approach to define such spatial and temporal boundaries.

The structure of the paper is as follows. The next section presents the motivation and research challenges. This is followed by a discussion of the related work in Section 2. The approach to representing the timestamped data is discussed in Section 4. Then Section 5 describes a logical framework comprising formal descriptions of space, time, events, processes, geographical objects and their related aspects. In Section 6 we introduce the semantic definition of a geographical process. Then Section 7 presents formal definitions for the set of process properties which we have proposed. Finally, Section 8 draws some conclusions and discusses further works.

2 Related Work

Processes have been investigated in different areas, such as Philosophy, Linguistics, Business and in several sub-areas of Computer Science. In Geographical Information Systems (GIS), different approaches have been developed to deal with processes, and an assorted terminology has been applied (e.g. *geo-processes*, *geo-phenomena*, *dynamic GIS*, *spatio-temporal GIS*). In the field of Knowledge Representation, *spatio-temporal reasoning* [7, 21] and *reasoning about spatio-temporal changes* [13] have been investigated. Theories involving *objects*, *events*, *states* and *process* have also become of interest [9, 12].

Some research in GIS has been presented as an approach to handling real-world phenomena, which appears in the literature under a variety of different names, such as *process models*, *reality-representation systems* and *modelling-systems*. Nonetheless, the development of such systems has been limited to a particular area of application (e.g. meteorology, traffic studies, population studies) and usually with the purpose of simulation and prediction. Examples can be found in [15, 20].

Galton [8] argues that a spatio-temporal geo-ontology must comprise appropriate forms of representation to do justice to both the *field-based* and *object-based* views of the world [10], extended appropriately to consider the temporal dimension. Additionally, it should provide different views of spatio-temporal extents, especially with reference to phenomena such as storms, floods and wildfires. Field-based approaches to simulating geographical processes have been proposed by using *cellular automata*. Examples can be found for simulation of wildfires [2, 14] and urban spreading [1, 20]. On the other hand, *agent-based models* have been suggested as an object-based approach to handling geographical processes. These models have been proposed, for example, to simulating landscape evolution [18], urban development [4] and traffic systems [6].

Some authors have also presented ontological approaches to representing geographical processes. For instance, Devaraju and Kuhn [5] present a process-centric ontology to represent relations between geographical processes and observed properties originated from Geo-Sensor Networks (GSNs), by defining a controlled terminology which allows an explicit representation of a process and its participants (i.e. physical objects and substances). However, this is distinct from the approach presented here, since it is mainly concerned with modelling geographical processes in terms of the interaction between their participants and the physical and chemical transformations involved in their execution, whereas this work draws more attention to the identification of geographical processes from spatial changes observed amongst geographical features over time.

3 Motivation and Research Challenges

A temporal series of spatial data representing evolving geographical features is often interpreted by humans in terms of geographical processes and their associated properties. Given a spatial region and a time interval of observation, distinct manifestations of a geographical process may be identified simultaneously in different sub-regions, or at different sub-intervals in the same sub-region. For example, a desertification process may accelerate in a subregion during a certain period of time, whilst another process of the same type proceeds steadily in another subregion during the same period. When dealing with reasonably large datasets, this dynamicity causes difficulties for humans to identify some manifestations of geographical processes. Therefore, the conceptualisation of dynamic geographical features and their correlation with geographical processes may provide an approach that can augment human's ability to analyse large spatio-temporal datasets.

Remote Sensing is an evolving research area which collects useful data about the physical world. A considerable amount of data produced is the result of digital processing of satellite imagery and aerial photography. These areas of research are mostly concerned with the identification and classification of different features that compose the geographical space, and frequently generate vector spatial data as an output, such as described in [17] and [19]. Moreover, temporal series of spatial data can be generated by producing images of a given region at different times. However, since this field of study is reasonably recent, many spatio-temporal datasets are still being produced and are not fully exploited in GIS. Therefore, this increasing availability of data reinforce the demand for efficient approaches to link such spatio-temporal data to a reasoning mechanism in order to investigate geographical processes.

The capability of defining precise instantiations of a process (both in space and in time) is a fundamental issue to provide a suitable approach to reasoning about its properties. A representational model which takes into account those questions needs to be flexible in consideration of different interpretations which may arise for some dynamic properties investigated. For example, to maintain that a deforestation process is accelerating in a given spatial region R and time interval I requires the definition of a 'deforestation expansion rate'. However, there may be distinct interpretations for this rate. For instance, it could relate the area of the portion of R deforested during I either to the previously existing deforested portion of R or to the total area of R. Also the rate could be measured in terms of absolute area or as a percentage.

Several approaches to reasoning about space and time and different methods of modelling geographical processes have been proposed, however, an approach to developing an ontology grounded upon a spatio-temporal data to reasoning about geographical processes and their spatio-temporal changing properties is still missing. Grounding an ontology upon the data requires work at multiple levels, both to select the appropriate set of predicates to be grounded and formulating a suitable representation for the data. In addition, a considerable amount of work on geometrical computation should be done to enable spatial predicates defined in the conceptual level to be interpreted at the data level.

4 Time-stamped Data

As stated before, we propose a logical framework which can be linked explicitly to a spatial-temporal dataset in order to develop practical applications. Spatio-temporal datasets are distributed in a variety of formats, which include aspects of geometrical representation of space, representation of temporal elements, scale, granularity and other important aspects. This Section presents our approach to the representation and storage of data in such a way that reasoning about dynamic geographical features is possible.

We present some relations which hold between different forms of data representation, in order to provide a way to derive implicit data in reduced datasets. They are described in terms of definitions and axioms in first order logic, indexed by D and A, respectively. In axioms, free variables are implicitly universally quantified with maximal scope. We employ the Region Connection Calculus (RCC) [16] as the theory of *space*, using the following spatial relations between spatial regions: *overlaps* $\mathsf{O}(x, y)$, *externally connected* $\mathsf{EC}(x, y)$ and *part of* $\mathsf{P}(x, y)$.

We assume a total linear reflexive ordering on *time*, and use explicit time variables t_i. These variables can be compared by equality ($t_1 = t_2$) and ordering ($t_1 < t_2$) relations and can be quantified over in the usual way ($\forall t[\phi(t)]$). In addition, the predicates $\mathsf{Instant}(s)$ and $\mathsf{Interval}(s)$ are employed to distinguish instants and intervals. We also use the functions $\mathsf{b}(i)$ and $\mathsf{e}(i)$, which return an instant corresponding to the beginning and the end of an interval i, respectively.

The data is stored as factual elements asserted in a knowledge base. Storing the data in a logical fashion allows us to derive implicit data and provides natural way to link the logical framework to the knowledge base. The spatio-temporal data consist of attributed polygons which are associated with timestamps. *Attributes* describe either types of region coverage (e.g. *forested, arid*) or types of geographical features (e.g. *forest, desert*). *Polygons* represent spatial regions or geographical features. We are particularly interested in geographical features which can be modelled as the maximal well-connected regions [1] of some particular coverage, as shall be discussed later in this Section. *Timestamps* are used to represent both time instants and time intervals. This data is structured as follows:

$\mathcal{D} \subseteq A \times P \times S$, where:

A is the set of attributes;

P is the set of two-dimensional simple[2] polygons;

S is the set of time instants and intervals, defined as:

$S = \{ \langle t_1, t_2 \rangle \mid t_1, t_2 \in T \wedge t_1 \leq t_2 \}$, where T is the set of timestamps;

According to this definition, an instant is represented by a zero-length interval (i.e. when $t_1 = t_2$).

A datum is a tuple assuming the form $\langle a, p, s \rangle$, where p is a polygon, a is an attribute and s is an instant or interval. These data elements are stored as asserted facts using the predicate *Spatio-temporal Attributed Region* $\mathsf{Star}(a, p, s)$. For readability, we use in this paper the predicate $\mathsf{A\text{-}Star}(a, p, s)$ to indicate

[1] The term 'well-connected region' is used here in a agreement with the discussion and definitions given in [3].

[2] A *simple polygon* is one whose boundary does not cross itself. However, in order to represent spatial regions which can have holes, the set S may contain *weakly simple polygons*, in which some sides can 'touch' but cannot 'cross over'. See `http://en.wikipedia.org/wiki/Simple_polygon` for further explanation and examples.

that the fact is *explicitly asserted* in the knowledge base, whereas the truth of Star(a,p,s) is determined by the semantics of attribute a and the geographic characteristics of the geo-referenced polygon 'p', whether or not it is actually asserted in the knowledge base. Consequently, we specify the axiom A1 to assure that $\mathsf{Star}(a,p,s)$ is true if the corresponding fact (explicitly asserted) is true.

A 1 $\mathsf{A\text{-}Star}(a,p,s) \rightarrow \mathsf{Star}(a,p,s)$

This data model currently supports the following types of attributes to be explicitly asserted in the knowledge base:

- $\mathsf{CAtt\text{-}Hom}(x)$ - *homogeneous coverage attributes* are applied to denote spatial regions which are regarded as covered by a single type of coverage.
- $\mathsf{CAtt\text{-}Het}(x)$ - *heterogeneous coverage attributes* are employed to denote spatial regions which may contain multiple types of coverage.
- $\mathsf{FAtt\text{-}Sim}(x)$ - *simple feature attributes* are applied to denote geographical features which cannot be composed by other geographical features and that every region which is part of it must have the same coverage.
- $\mathsf{FAtt\text{-}Com}(x)$ - *compound feature attributes* are applied to denote geographical features which may be composed by other geographical features or that may contain regions with different coverages.

However, the semantic model (which shall be discussed later in this paper) currently focus on geographical processes which affect simple features. For this reason, this paper draws particular attention to the attributes $\mathsf{CAtt\text{-}Hom}(x)$ and $\mathsf{FAtt\text{-}Sim}(x)$.

More general predicates for attribute types are defined in D1, D2 and D3: *coverage attribute* $\mathsf{CAtt}(x)$, *feature attribute* $\mathsf{FAtt}(x)$ and *attribute* $\mathsf{Att}(x)$, respectively.

D 1 $\mathsf{CAtt}(x) \equiv_{def} \mathsf{CAtt\text{-}Hom}(x) \ \vee \ \mathsf{CAtt\text{-}Het}(x)$

D 2 $\mathsf{FAtt}(x) \equiv_{def} \mathsf{FAtt\text{-}Sim}(x) \ \vee \ \mathsf{FAtt\text{-}Com}(x)$

D 3 $\mathsf{Att}(x) \equiv_{def} \mathsf{CAtt}(x) \ \vee \ \mathsf{FAtt}(x)$

We can now specify the axiom A2 which relates the predicate $\mathsf{Star}(a,p,s)$ to the elements to which it applies. In this axiom, we use the predicate $\mathsf{Polygon}(p)$ to assert that p is a two-dimensional simple polygon.

A 2 $$\mathsf{Star}(a,p,s) \ \rightarrow \ \mathsf{Polygon}(p) \ \wedge \ \mathsf{Att}(a) \quad \wedge \\ (\mathsf{Instant}(s) \vee \mathsf{Interval}(s))$$

The axiom A3 restricts the cases where part-hood relations may hold involving STAR elements.

A 3 $$\mathsf{Star}(a_1,p_1,s) \ \wedge \ \mathsf{Star}(a_2,p_2,s) \ \wedge \ \mathsf{P}(p_1,p_2) \ \wedge \\ (\mathsf{FAtt\text{-}Sim}(a_2) \ \vee \ \mathsf{CAtt\text{-}Hom}(a_2)) \ \rightarrow \ \mathsf{CAtt\text{-}Hom}(a_1)$$

A variety of geospatial information may be represented using $STAR$ relations. However, we define axioms which restrict the data model to deal with a set of useful kinds of representations which are currently supported by our semantic model. When a $STAR$ element is associated with a time instant, it represents a snapshot of a spatial region or geographical feature at this time point. On the other hand, when this element is associated with a time interval, it denotes either a spatial region whose coverage has been entirely changed during such interval or a geographical feature which has been created during the specified interval (and did not exist before the interval). These forms of representing data elements enable our model to use datasets distributed using different approaches to represent the data, i.e., containing different combinations of these types of data elements. Thus we shall discuss how these elements are related so that it is possible to deduce implicit data from limited datasets.

We employ the logical relation $\mathsf{Can\text{-}Include}(a_1, a_2)$ to associate either homogeneous and heterogeneous coverage attributes; or *coverage attributes* and *feature attributes*. These relationships must be explicitly asserted as facts in the knowledge base. The former case ensures that a homogeneous region whose coverage type is denoted by a_1 can be part of a heterogeneous region whose coverage type is denoted by a_2. The latter case assures that a region whose coverage is denoted by the attribute a_1 can be part of a feature whose type is denoted by the attribute a_2. The axioms A4 to A6 are specified to ensure the properties of this relation are preserved.

A 4 $\mathsf{Can\text{-}Include}(a_1, a_2) \rightarrow (\mathsf{CAtt\text{-}Hom}(a_1) \wedge \mathsf{CAtt\text{-}Het}(a_2)) \vee (\mathsf{CAtt}(a_1) \wedge \mathsf{FAtt}(a_2))$

A 5 $\mathsf{Star}(a_1, p_1, s) \wedge \mathsf{Star}(a_2, p_2, s) \wedge \mathsf{CAtt\text{-}Hom}(a_1) \wedge \mathsf{CAtt\text{-}Het}(a_2) \wedge \mathsf{P}(p_1, p_2) \rightarrow \mathsf{Can\text{-}Include}(a_1, a_2)$

A 6 $\mathsf{Star}(a_1, p_1, s) \wedge \mathsf{Star}(a_2, p_2, s) \wedge \mathsf{CAtt}(a_1) \wedge \mathsf{FAtt}(a_2) \wedge \mathsf{P}(p_1, p_2) \rightarrow \mathsf{Can\text{-}Include}(a_1, a_2)$

An additional axiom is specified for the case when this relation is applied to associate *homogeneous coverage attributes* and *simple feature attributes*, in order to preserve the properties of homogeneity and simplicity assigned to these types of attributes, respectively.

A 7 $(\mathsf{Can\text{-}Include}(a_1, a_2) \wedge \mathsf{CAtt\text{-}Hom}(a_1) \wedge \mathsf{FAtt\text{-}Sim}(a_2)) \leftrightarrow \forall a[\exists p_1 p_2 s[\mathsf{Star}(a_1, p_1, s) \wedge \mathsf{Star}(a, p_2, s) \wedge \mathsf{P}(p_1, p_2) \wedge \mathsf{FAtt\text{-}Sim}(a)] \rightarrow a = a_2]$

The axioms A8 and A9 are also specified to ensure that a *simple feature attribute* must be related to one (and only one) *homogeneous coverage attribute*.

A 8 $\mathsf{FAtt\text{-}Sim}(a) \rightarrow \exists a'[\mathsf{CAtt\text{-}Hom}(a') \wedge \mathsf{Can\text{-}Include}(a', a)]$

A 9 $\mathsf{Can\text{-}Include}(a_1, a_2) \wedge \mathsf{FAtt\text{-}Sim}(a_2) \leftrightarrow \mathsf{CAtt\text{-}Hom}(a_1) \wedge \neg\exists a[(\mathsf{Can\text{-}Include}(a, a_2) \wedge a \neq a_1)]$

We have stated that many geographical features can be modelled as the maximal well-connected regions of some particular coverage. This is specified using the axiom A10.

A 10 $\mathsf{A\text{-}Star}(a,p,s) \wedge \mathsf{FAtt\text{-}Sim}(a) \leftrightarrow$
$$\neg\exists p'a'[\,\mathsf{Star}(a',p',s) \wedge \mathsf{CAtt\text{-}Hom}(a') \wedge \mathsf{Can\text{-}Include}(a',a) \wedge \mathsf{PP}(p,p')\,]$$

A geographical feature also denotes a spatial region with the same spatial extension. In case it is a simple geographical feature, such region is also associated to the related type of coverage.

A 11 $\mathsf{A\text{-}Star}(a,p,s) \wedge \mathsf{FAtt\text{-}Com}(a) \rightarrow \mathsf{Star}(a',p,s) \wedge \mathsf{CAtt\text{-}Het}(a')$

A 12 $\mathsf{A\text{-}Star}(a,p,s) \wedge \mathsf{FAtt\text{-}Sim}(a) \rightarrow$
$$\mathsf{Star}(a',p,s) \wedge \mathsf{CAtt\text{-}Hom}(a') \wedge \mathsf{Can\text{-}Include}(a',a)$$

If two spatial regions with the same coverage are externally connected, then their spatial sum also denote a spatial region.

A 13 $\mathsf{Star}(a,p_1,s) \wedge \mathsf{Star}(a,p_2,s) \wedge \mathsf{CAtt}(a) \wedge \mathsf{EC}(p_1,p_2) \rightarrow$
$$\mathsf{Star}(a,p',s) \wedge p' = \mathsf{external\text{-}boundary}(\mathsf{sum}(p_1,p_2))$$

Given a spatial region r, every sub-region r' of r is also a region (with the same coverage of r, in the case of regions with homogeneous coverage).

A 14 $\mathsf{Star}(a,p_1,s) \wedge \mathsf{CAtt\text{-}Het}(a) \rightarrow$
$$\forall p'[\,\mathsf{P}(p',p) \rightarrow \mathsf{Star}(a',p',s) \wedge (\mathsf{CAtt\text{-}Hom}(a') \vee \mathsf{CAtt\text{-}Het}(a'))\,]$$

A 15 $\mathsf{Star}(a,p,s) \wedge \mathsf{CAtt\text{-}Hom}(a) \rightarrow \forall p'[\,\mathsf{P}(p',p) \rightarrow \mathsf{Star}(a,p',s)\,]$

Some attributes may be regarded as non-intersectacle. It means that two spatial regions (or geographical features, or any combination of them) cannot be overlapped at a certain time instant if they are associated with non-intersectable attributes. For instance, one can say that a *arid* region and a *forest* feature cannot share the same spatial extension at the same time. These relationships are explicitly asserted as facts in the knowledge base, excepting for relating any combination of homogeneous coverage attributes and simple features, which are naturally non-intersectable (this is assured by the axioms A12 and A16). This relation is defined as follows.

D 4 $\mathsf{No\text{-}Intersection}(a_1,a_2) \equiv_{def}$
$$\mathsf{Att}(a_1) \wedge \mathsf{Att}(a_2) \wedge a_1 \neq a_2 \wedge \forall p_1 p_2 s[\,\mathsf{Instant}(s) \wedge \mathsf{Star}(a_1,p_1,s) \wedge \mathsf{Star}(a_2,p_2,s) \rightarrow \neg O(p_1,p_2)\,]$$

A 16 $\mathsf{CAtt\text{-}Hom}(a_1) \wedge \mathsf{CAtt\text{-}Hom}(a_2) \rightarrow \mathsf{No\text{-}Intersection}(a_1,a_2)$

We have stated that when a *STAR* element is applied to a time interval it may represent the complete change of coverage in a spatial region or the entire creation of a geographical feature during a time interval. However, it may imply changes in other regions and features existing just before such interval and with which the new region cannot be intersected. For example, consider that the fact $\mathsf{No\text{-}Intersection}(forested, urbanized)$ is asserted in the knowledge base. In addition, suppose a dataset consisting of $\mathsf{Star}(a, p, i)$ elements representing urbanized regions created over regular time intervals (e.g. a week). Then, when some of these regions intersects a region which was forested at t_1 (where $t_1 = begin(i) - 1$), a new snapshot of this forested region at t_2 (where $t_2 = end(i)$) can be deduced if it is not stored explicitly in the database (assuming that the forested region at t_1 is also given). This is assured by the axioms A17 and A18.

A 17 $$\mathsf{A\text{-}Star}(a,p,s) \wedge \mathsf{Interval}(s) \rightarrow \mathsf{Star}(a,p,\mathsf{e}(s)) \quad \wedge \\ \neg\exists p'[\,P(p',p) \wedge \mathsf{Star}(a,p',t_1) \wedge t_1 = \mathsf{b}(s) - 1\,] \quad \wedge \\ \neg\exists a'p't[\,\mathsf{Star}(a',p',t) \wedge \mathsf{No\text{-}Intersection}(a,a') \quad \wedge \\ t = \mathsf{e}(s) \wedge \mathsf{O}(p,p')\,]$$

A 18 $$\mathsf{Star}(a,p,t_1) \wedge \mathsf{Instant}(t_1) \wedge \mathsf{Interval}(i) \wedge t_1 = \mathsf{b}(i) - 1 \quad \wedge \\ \neg\exists a'p'[\,\mathsf{Star}(a',p',i) \wedge \mathsf{No\text{-}Intersection}(a,a') \wedge \mathsf{O}(p,p')\,] \\ \rightarrow \mathsf{Star}(a,p,t_2) \wedge \mathsf{e}(i)$$

We have shown different forms of data representation and the relationship between them, so that it is possible to deduce implicit data in reduced datasets. Although these implicit data can be deduced in the logical level (at reasoning time), a more efficient approach is to generate and store part of these explicitly, so that it can accessed more quickly as asserted facts at reasoning time. To define which data should be stored, we should consider both the processing time of generation and the storage space needed. In our implementation, depending on the type of data available to be used as input for the system, we submit them to a mechanism which enrich the original dataset by storing the following deduced data explicitly: maximal well-connected regions of some particular coverage, representing geographical features; and regions which has been changed as a consequence of the creation of other non-intersectable regions over a interval.

5 Logical Framework

We now present a logical framework we have named *RGP*, which is an acronym for *Reasoning about Geographical Processes*, comprising formal descriptions of space, time, events, processes, geographical objects (features) and their related aspects. This Section describes the basic syntax and semantics of the logical language employed in the framework. This language has been named $\mathfrak{R}$. Relevant predicates and logical relations employed in this framework shall be introduced in Sections 6 and 7.

The current version of this framework is restricted to dealing with processes which affects *homogeneous coverage regions* and *simple feature*. Future works shall include semantics to deal with different types of geographical data which is already supported by the data model described in Section 4. In this semantic model, we use the elements of type *feature type* and *regions coverage type* to represent possible types of region coverage attributes and feature attributes existing in the data model.

Events and processes are structured in terms of *types* and *tokens*. Event-types denote a certain kind of change which may affect a certain type of geographical feature. On the other hand, event-tokens denote particular occurrences of event types. These tokens are therefore associated with a specific time interval and a specific instance of a feature. For example, we may specify an event-type 'forest expansion' and an event-token to denote 'the expansion of the Amazon forest occurred between 01/01/2001 and 31/12/2001'. Similarly, process-types denotes a series of changes which take place in a certain feature-type, whilst a process-token denotes a particular instance of this type of process. Therefore tokens are said to *proceed* during a specific time interval and in a specific instance of a feature.

5.1 Syntax

The logical language $\Re$ used in the framework comprises variables of 10 *nominal types* which can be quantified over. The vocabulary of $\Re$ can be specified by a tuple $\mathcal{V} = \langle \mathcal{T}, \mathcal{I}, \mathcal{R}, \mathcal{F}, \mathcal{E}, \Sigma, \mathcal{P}, \Gamma, \mathcal{O}, \mathcal{L} \rangle$. These types and the variables used to assign them are listed below:

- Time Instants, $\mathcal{T} = \{..., t_i, ...\}$
- Time Intervals, $\mathcal{I} = \{..., i_i, ...\}$
- Spatial Regions, $\mathcal{R} = \{\varnothing, ..., r_i, ...\}$
- Geographical Features, $\mathcal{F} = \{..., f_i, ...\}$
- Event-types, $\mathcal{E} = \{..., e_i, ...\}$
- Event-tokens, $\Sigma = \{..., \sigma_i, ...\}$
- Process-types, $\mathcal{P} = \{..., \rho_i, ...\}$
- Process-tokens, $\Gamma = \{..., \gamma_i, ...\}$
- Homogeneous Coverage Type, $\mathcal{O} = \{..., o_i, ...\}$
- Simple Feature Type, $\mathcal{L} = \{..., l_i, ...\}$

The following *logical functions* are used to transfer information between distinct semantic types:

- $\mathsf{b}(i)$ and $\mathsf{e}(i)$ return, respectively, the time instant corresponding to the beginning and the end of the interval i.
- $\mathsf{dur}(\sigma)$ gives the interval of occurrence of the event-token e.
- $\mathsf{ext}(f)$ returns a spatial region with the same spatial extension of a feature f.
- $\mathsf{f\text{-}type}(f)$ gives the type of the specified feature.
- $\mathsf{c\text{-}type}(r)$ returns the coverage type of the specified spatial region.

Several *predicates* and *logical relations* are also employed. They are described below:

- $t_1 < t_2$, $t_1 = t_2$, $t_1 \leq t_2$ are true, respectively, just in case the time term t_1 denotes a time earlier than the time denoted by t_2; t_1 denotes a time equal to t_2; t_1 denotes a time equal to or earlier than t_2.
- The following RCC relations between spatial regions: *connected* $\mathsf{C}(\alpha, \beta)$, *disconnected* $\mathsf{DC}(\alpha, \beta)$, *overlaps* $\mathsf{O}(\alpha, \beta)$, *externally connected* $\mathsf{EC}(\alpha, \beta)$, *part of* $\mathsf{P}(\alpha, \beta)$, *proper part of* $\mathsf{PP}(\alpha, \beta)$ and *equals to* $\mathsf{EQ}(\alpha, \beta)$, where α and β are region terms which may be either a region variable r_i, a term of the form $\mathsf{ext}(f_i)$ or the empty region constant $\varnothing$.
- $\mathsf{Holds\text{-}At}(\varphi, t)$ relation asserts that formula φ is true at the time instant denoted by t.
- $r_1 =_c r_2$, $r_1 \neq_c r_2$ are true, respectively, just in case the spatial region term r_1 denotes a region with the same type of coverage of region denoted by r_2; r_1 denotes a region with different type of coverage of r_2.

We also define the operator $f_1 \doteq f_2$, which is true if f_1 and f_2 are geographical features which have the same trans-world identity criteria. The identity criteria for a feature is defined in terms of the connectivity of its spatial extension over a time interval.

D 5

$$\begin{aligned} f_1 \doteq f_2 \leftrightarrow \forall it[\, \mathsf{b}(i) < t \leq \mathsf{e}(i) \wedge \mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f_1), r_1), t-1) \quad \wedge \\ \mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f_2), r_2), t) \rightarrow \\ \mathsf{C}(r_1, r_2) \wedge \neg\exists r_3[\, r_1 =_c r_2 =_c r_3 \quad \wedge \\ \mathsf{DC}(r_3, r_2) \wedge \mathsf{DC}(r_3, r_1)\,]\,] \end{aligned}$$

The following auxiliary functions are also employed to perform spatial calculations.

- $\mathsf{sum}(D)$ returns a spatial region which corresponds to the spatial sum of a set D of spatial regions.
- $\mathsf{area}(r)$ returns a number representing the area of a region r.

If φ and ψ are propositions of $\Re$, then so are the following:

- $\neg\varphi$, $(\varphi \wedge \psi)$, $(\varphi \vee \psi)$, $(\varphi \rightarrow \psi)$, $\forall \upsilon[\varphi]$

Where υ is a variable of one of the nominal types described earlier.

5.2 Semantics

An *attributed geographic model* (AGM) is a structure $\mathcal{M} = \langle \mathfrak{G}, \mathcal{V}, \mathcal{A} \rangle$, where:

- $\mathfrak{G} = \langle \mathbb{R}^2, \langle T, \preceq \rangle, A, \mathcal{D} \rangle$ is a formal model of a geographic dataset:

  - $\mathbb{R}^2$ is the real plane, which will represent the geogrpahic surface,[3]
  - T is a set of time points,
  - $\preceq$ is a total linear order over T,
  - A is a set of geographic attributes,
  - $\mathcal{D} \subseteq A \times \mathsf{Poly}(\mathbb{R}^2) \times \mathsf{Int}(T)$ represents the geographic attribute data as a set of tuples of the form $\langle a, p, s\rangle$, which correspond to the fact that attribute a holds for polygon p over interval s.[4]
    Here, $\mathsf{Poly}(\mathbb{R}^2)$ is the set of well-connected polygons over $\mathbb{R}^2$, and $\mathsf{Int}(T) = \{\langle t_1, t_2\rangle \mid t_1, t_2 \in T \wedge t_1 \preceq t_2\}$ is the set of all intervals over the time sequence $\langle T, \preceq\rangle$.
- $\mathcal{V} = \langle \mathcal{T}, \mathcal{I}, \mathcal{R}, \mathcal{F}, \mathcal{E}, \Sigma, \mathcal{P}, \Gamma, \mathcal{O}, \mathcal{L}\rangle$, specifies the vocabulary of our reprentation language. Each element of this tuple is the set of all symbols of a given type (as specified in the syntax setion).
- $\mathcal{A} = \langle a_\mathcal{T}, a_\mathcal{I}, a_\mathcal{R}, a_\mathcal{F}, a_\mathcal{E}, a_\Sigma, a_\mathcal{P}, a_\Gamma, a_\mathcal{O}, a_\mathcal{L}\rangle$ is a tuple of assignment functions specifying the denotations of all symbols in the vocabulary as follows:
  - $a_\mathcal{T} : \mathcal{T} \to T$, maps time point variables to timepoints.
  - $a_\mathcal{I} : \mathcal{I} \to \mathsf{Int}(T)$, maps interval variables to intervals.
  - $a_\mathcal{R} : \mathcal{R} \to \mathsf{Reg} - \mathsf{Closed}(\mathbb{R}^2)$, maps region variables to regular closed regions of the plane,[5]
  - $a_\mathcal{F} : \mathcal{F} \to (T \to \mathsf{Poly}(\mathbb{R}))$, maps each feature symbol to a function from time points to polygons (giving the spatial extension of the feature at each time point).
  - $a_{\mathcal{E}\mathcal{F}} : (\mathcal{E} \times \mathcal{F}) \to 2^S$, maps each combination of an event type symbol and a feature symbol to a set of intervals. These are the intervals during which there is an occurence of the event type involving that feature.
  - $a_\Sigma : \Sigma \to (\mathcal{E} \times \mathcal{F} \times \mathsf{Int}(T))$, maps each event token symbol to a triple consisting of an event type, a feature (the participant) and an interval (the interval over which this particular event token occurs).
  - $a_\mathcal{P} : \mathcal{P} \to ?$, — process types.
  - $a_\Gamma : \Gamma \to ?$, — process tokens.
  - $a_\mathcal{O} : \mathcal{O} \to (T \to \mathsf{Reg} - \mathsf{Closed}(\mathbb{R}^2))$, maps homogeneous cover attributes to functions from time points to regular closed regions of the plane. This gives the extension of the cover feature at each time point. In general this will be a multi-piece region.
  - $a_\mathcal{L} : \mathcal{L} \to (T \to 2^{\mathsf{Poly}(\mathbb{R})})$ maps each simple feature type to a function from time points to sets of polygons.

[3] Clearly, one might want to use a different coordinate system or a 2.5D surface model. For simplicity we just assume that the space is modelled by $\mathbb{R}^2$ but this could easily be changed without much modification to the rest of the semantics. It would affect the way that topological and metric properties are computed from the data, but our formal does not specify such implementation details.

[4] An interval may be *punctual*, if its beginning is the same as its end. Such intervals correspond to a single time points.

[5] We could probably use multi-polygons, instead of regular closed regions. This might be better, since we may not need to refer to regular-closed regions that are not polygonal.

6 Geographical Process Definition

6.1 Events

An event-type can be represented using the following predicate.

$\mathsf{Event\text{-}Type}(e)$

An event-token is represented in terms of its type and participant, using the relation specified below.

$\sigma = \mathsf{Event}(e, f)$

The relation between event-token and its participant is defined as follows.

D 6 $\mathsf{Participant\text{-}E}(\sigma, f) \equiv_{def} \exists\sigma[\,\sigma = \mathsf{Event}(e, f)\,]$

We now define the relation between event-type and event-token.

D 7 $\mathsf{Event\text{-}Is\text{-}Of\text{-}Type}(\sigma, e) \equiv_{def} \exists f[\,\sigma = \mathsf{Event}(e, f)\,]$

We distinguish events which are purely spatial from others which are conceived as a geographical event. For example, the *shrinkage* of geographical features in general is considered a purely spatial event. However, when such shrinkage is associated with a specific type of feature it may be conceived as a geographical event. For example, when a feature *forest* shrinks, it may be interpreted as a geographical event, that is, a *deforestation* event. Therefore we define Event-types in terms of possible sub-types, i.e. *spatial change events* and *geographical events*:

D 8 $\mathsf{Event\text{-}Type}(e) \equiv_{def} \mathsf{Sp\text{-}Change\text{-}Event}(e) \vee \mathsf{Geo\text{-}Event}(e)$

We now define a relation which associates a spatial change event e_c, a geographical event e_g and a feature-type l. It means that when e_c occurs in a feature of type l it denotes the occurrence of a geographical event e_g.

D 9
$$\begin{aligned}&\mathsf{Event\text{-}Feature}(e_c, l, e_g) \equiv_{def}\\ &\quad \mathsf{Sp\text{-}Change\text{-}Event}(e_c) \wedge \mathsf{Geo\text{-}Event}(e_g) \quad \wedge\\ &\quad (\mathsf{Occurs}(\sigma_1, i) \wedge \sigma_1 = \mathsf{Event}(e_c, f) \wedge l = \mathsf{f\text{-}type}(f) \quad \rightarrow\\ &\quad \mathsf{Occurs}(\sigma_2, i) \wedge \sigma_2 = \mathsf{Event}(e_g), f))\end{aligned}$$

The relation defined below is employed to associate two events which are interpreted as opposite each other, for example a *forestation event* and *deforestation event*.

D 10
$$\begin{aligned}\mathsf{Reverse\text{-}E}(e_1, e_2) \rightarrow\ &(\mathsf{Sp\text{-}Change\text{-}Event}(e_1) \wedge \mathsf{Sp\text{-}Change\text{-}Event}(e_2))\\ &\vee \quad (\mathsf{Geo\text{-}Event}(e_1) \wedge \mathsf{Geo\text{-}Event}(e_2))\end{aligned}$$

The following axiom assures the symmetry property for this relation.

A 19 $\mathsf{Reverse\text{-}E}(e_1, e_2) \leftrightarrow \mathsf{Reverse\text{-}E}(e_2, e_1)$

For readability, we use this relation as a logical function

$e_2 = \mathsf{reverse\text{-}e}(e_1)$

Then we can now specify an axiom to ensure the integrity of the relation $\mathsf{Event\text{-}Feature}(e_c, l, e_g)$ when applied to reverse events.

A 20 $\mathsf{Event\text{-}Feature}(e_c, l, e_g) \leftrightarrow$
$\mathsf{Event\text{-}Feature}(\mathsf{reverse\text{-}e}(e_c), l, \mathsf{reverse\text{-}e}(e_g))$

6.2 Processes

We model a process as a 'chunking' of events of the same type involving the same participant. We define some predicates and relation for processes which are similar to those defined for events, as follows.

A process-type can be represented using the following predicate.

$\mathsf{Process\text{-}Type}(\rho)$

A process-token is represented in terms of its type and participant, using the relation:

$\gamma = \mathsf{Process}(\rho, f)$,

The relation between process-token and its participant is defined as follows.

D 11 $\mathsf{Participant\text{-}P}(\gamma, f) \equiv_{def} \exists\gamma[\, \gamma = \mathsf{Process}(\rho, f)\,]$

We now define the relation which associates a process-token with a process-type.

D 12 $\mathsf{Process\text{-}Is\text{-}Of\text{-}Type}(\gamma, \rho) \equiv_{def} \exists f[\, \gamma = \mathsf{Process}(\rho, f)\,]$

We define the concept of *reverse process* which is analogous to the concept of reverse events. The following relation is applied to associate two opposite process types.

$\mathsf{Reverse\text{-}P}(\rho_1, \rho_2)$

The following axiom assures the symmetry property for this relation.

A 21 $\mathsf{Reverse\text{-}P}(\rho_1, \rho 2) \leftrightarrow \mathsf{Reverse\text{-}P}(\rho_2, \rho_1)$

As defined for events, for readability, we also use this relation as a *logical function*.

$\rho_2 = \mathsf{reverse\text{-}p}(\rho_1)$

The relation *Event Moves Process Forwards* associates an event-type with a process-type. Asserting a fact using this relation means that if a process of type ρ is characterised by occurrences of events of type e, the process moves forwards.

$\mathsf{EMPF}(e, \rho)$

Similarly, the relation *Event Moves Process Backwards* means that a process of type ρ moves backwards if it is characterised by occurrences of events of type e.

$\mathsf{EMPB}(e, \rho)$

The axioms A22, A23 and A24 assure that the relations EMPF and EMPB are valid for reverse events and process.

A 22 $\mathsf{EMPF}(e, \rho) \leftrightarrow \mathsf{EMPB}(\mathsf{Reverse\text{-}E}(e), \rho)$

A 23 $\mathsf{EMPF}(e, \rho) \leftrightarrow \mathsf{EMPB}(e, \mathsf{Reverse\text{-}P}(\rho))$

A 24 $\mathsf{EMPF}(e, \rho) \leftrightarrow \mathsf{EMPF}(\mathsf{Reverse\text{-}E}(e), \mathsf{Reverse\text{-}P}(\rho))$

We can now present our approach to define when if a process proceeds.

D 13 $\mathsf{Proceeds}(\gamma) \equiv_{def} \gamma = \mathsf{Process}(\rho, f), i) \wedge \forall t[\, \mathsf{b}(i) < t \leq \mathsf{e}(i) \wedge \exists i_{sub} e[\, t-1 = \mathsf{b}(i_{sub}) \wedge t = \mathsf{e}(i_{sub}) \wedge \mathsf{Occurs}(\mathsf{Event}(e, f), i_{sub}) \wedge \mathsf{EMPF}(e, \rho)\,]\,]$

Similarly, we may also define the *active* predicate in terms of the reverse process and the EMPB relation, as follows.

D 14 $\mathsf{Proceeds}(\gamma) \equiv_{def} \gamma = \mathsf{Process}(\mathsf{reverse\text{-}p}(\rho), f), i) \wedge \forall t[\, \mathsf{b}(i) < t \leq \mathsf{e}(i) \wedge \exists i_{sub} e[\, t-1 = \mathsf{b}(i_{sub}) \wedge t = \mathsf{e}(i_{sub}) \wedge \mathsf{Occurs}(\mathsf{Event}(e, f), i_{sub}) \wedge \mathsf{EMPB}(e, \rho)\,]\,]$

The relation *Process Component* is true in case an event σ is said to be a component of a process γ. This is defined as follows.

D 15 $\mathsf{Proc\text{-}Comp}(\sigma, \gamma) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \wedge \mathsf{Occurs}(\sigma, i) \wedge \mathsf{b}(i) \leq \mathsf{b}(i_{sub}) \leq \mathsf{e}(i_{sub}) \leq \mathsf{e}(i) \wedge \mathsf{Participant} - \mathsf{E}(\sigma, f) \wedge \mathsf{Participant} - \mathsf{P}(\gamma, f)$

7 Defining Properties of Processes

In this section we present approaches to represent properties of processes. We describe a set of properties which may be applied to a variety of geographical processes: Initiation, Cessation, Acceleration, Deceleration and Constant Proceeding.

7.1 Process Initiation and Cessation

Once defined the predicate $\mathsf{Proceeds}(\gamma, i)$, which delimits temporal boundaries of a process instance, the definition of process initiation and cessation is straightforward. This is as follows.

D 16 $\mathsf{Initiation}(\gamma, t) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \wedge t = b(i)$.

D 17 $\mathsf{Cessation}(\gamma, t) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \wedge t = e(i)$.

7.2 Process Acceleration, Deceleration and Constant Proceeding

A process acceleration, deceleration and constant proceeding may be defined in many forms, which depend on the type of geographical process being investigated and which spatial process is associated to their activity. We now present an approach to define these properties applied to geographical processes whose activities are based on the expansion and shrinkage of geographical features.

Spatial Expansion and Shrinkage events are defined in terms of mereological relationships between the spatial extension of a feature before and after the occurrence of such event. This is as follows.

D 18 $\mathsf{Occurs}(\mathsf{Event}(expansion, f), i) \equiv_{def}$
$\mathsf{Holds\text{-}At}(\mathsf{ext}(f) = r_1, \mathsf{b}(i) - 1) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{ext}(f) = r_2, \mathsf{e}(i)) \quad \wedge$
$(\mathsf{PP}(r_b, r_e) \vee \mathsf{PO}(r_b, r_e) \vee \mathsf{EC}(r_b, r_e))$

D 19 $\mathsf{Occurs}(\mathsf{Event}(shrinkage, f), i) \equiv_{def}$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_b), \mathsf{b}(i) - 1) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_e), \mathsf{e}(i)) \quad \wedge$
$(\mathsf{PP}(r_e, r_b) \vee \mathsf{PO}(r_b, r_e) \vee \mathsf{EC}(r_b, r_e))$

Expansion and Shrinkage Rates should be defined in order to define process properties of acceleration, deceleration and constant proceeding. These rates could be defined in several ways, such as in terms of measurement of absolute area or as a percentage. We now present an approach to calculate these rates. Then it shall be employed to illustrate how we can define these process properties. We specify a generic relation $\mathsf{Rate}(\sigma, x)$, which assigns to x the rate calculated for a spatial change event σ.

Expansion Rate

D 20 $\mathsf{Rate}(\sigma, x) \leftarrow$
$\mathsf{Occurs}(\mathsf{Event}(expansion, f), i) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_b), \mathsf{b}(i) - 1) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_e), \mathsf{e}(i)) \quad \wedge$
$D = \{ r_1, r_2, ..., r_n \mid \neg \mathsf{P}(r_i, r_b) \wedge \mathsf{P}(r_i, r_e)\} \quad \wedge$
$x = (\mathsf{area}(\mathsf{sum}(D))/\mathsf{area}(r_b))$

Shrinkage Rate

D 21 $\mathsf{Rate}(\sigma, x) \leftarrow$
$\mathsf{Occurs}(\mathsf{Event}(shrinkage, f), i) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_b), \mathsf{b}(i) - 1) \quad \wedge$
$\mathsf{Holds\text{-}At}(\mathsf{EQ}(\mathsf{ext}(f), r_e), \mathsf{e}(i)) \quad \wedge$
$D = \{ r_1, r_2, ..., r_n \mid \mathsf{P}(r_i, r_b) \wedge \neg \mathsf{P}(r_i, r_e)\} \quad \wedge$
$x = (\mathsf{area}(\mathsf{sum}(D))/\mathsf{area}(r_b))$

Process Acceleration, Deceleration and Constant Proceeding can now be defined by using the relation we provided to calculate the changing rate for the required spatial change events. These properties can be applied to any geographical process which is composed by geographical events denoted by the occurrence of such spatial change events. These properties are defined as follows.

D 22 $\mathsf{acceleration}(\gamma, i) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \quad \wedge$
$\mathsf{Proc\text{-}Comp}(\sigma_1, \gamma) \wedge \mathsf{Proc\text{-}Comp}(\sigma_2, \gamma) \quad \wedge$
$\mathsf{e}(\mathsf{dur}(\sigma_1)) < \mathsf{e}(\mathsf{dur}(\sigma_2)) \quad \wedge$
$\mathsf{Rate}(\sigma_1, x_1) \wedge \mathsf{Rate}(\sigma_2, x_2) \rightarrow x_2 > x_1$

D 23 $\mathsf{deceleration}(\gamma, i) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \quad \wedge$
$\mathsf{Proc\text{-}Comp}(\sigma_1, \gamma) \wedge \mathsf{Proc\text{-}Comp}(\sigma_2, \gamma) \quad \wedge$
$\mathsf{e}(\mathsf{dur}(\sigma_1)) < \mathsf{e}(\mathsf{dur}(\sigma_2)) \quad \wedge$
$\mathsf{Rate}(\sigma_1, x_1) \wedge \mathsf{Rate}(\sigma_2, x_2) \rightarrow x_2 < x_1$

D 24 $\mathsf{constant}(\gamma, i) \equiv_{def} \mathsf{Proceeds}(\gamma, i) \quad \wedge$
$\mathsf{Proc\text{-}Comp}(\sigma_1, \gamma) \wedge \mathsf{Proc\text{-}Comp}(\sigma_2, \gamma) \quad \wedge$
$\mathsf{e}(\mathsf{dur}(\sigma_1)) < \mathsf{e}(\mathsf{dur}(\sigma_2)) \quad \wedge$
$\mathsf{Rate}(\sigma_1, x_1) \wedge \mathsf{Rate}(\sigma_2, x_2) \rightarrow x_1 = x_2$

8 Conclusions and Further Work

We have presented a representational model and a reasoning mechanism to analyse evolving geographical features and their relationship to geographical processes, in order to identify manifestations of certain properties which may be ascribed to these processes. We also described an approach to modelling the spatio-temporal data upon which the logical framework is grounded. This approach provides flexibility for storing datasets distributed in a variety of formats.

Further investigations shall be conducted in order to add the capability of storing spatial elements of several kinds of geometrical types, instead of restricting to polygonal types.

We introduce a set of properties which can be associated with several geographical processes, however future works shall include additional properties which should also be applicable to a variety of processes. The current version of the logical framework presented in this paper is restricted to dealing with processes which affects homogeneous coverage regions and simple features. Therefore, further works shall enrich its semantics to deal with different types of geographical data which is already supported by the proposed data model.

Of particular interest for further works is the incorporation of approaches to handling vagueness in the proposed reasoning mechanism. Geographical processes may be affected by vagueness in many ways, specially to defining spatial and temporal boundaries tanking into account different possible interpretations. This includes issues related to spacial and temporal aggregation and the treatment of information granularity.

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