A qualitative inference method for prediction of geographic process using spatial and temporal relations

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Abstract: Knowledge engineering is the systematic self-disciplined set of activities involved in design and development of knowledge-based systems. Abstraction of the real world into codified information is the objective of knowledge representation (KR). The survey of various works of researchers in the domain of spatio-temporal knowledge representation for reasoning real world actions in geographic applications is presented. Geographic event attributed spatial entity (GEASE) knowledge-base that will aid in reasoning events causing the spatial change in geographic features over the period of time is proposed. GEASE knowledge-base describing a spatial entity by considering the temporal event as an attribute is constructed to infer events that cause geographical changes. As a result, the significance of the proposed knowledge-base is illustrated by evaluating event based queries on synthetic dataset. Finally, we conclude the work with direction to enhance the logical formulation for its implementation on real datasets in future.

Keywords: knowledge representation; spatio-temporal reasoning; geographic information system; GIS; events; processes; prediction.

Reference to this paper should be made as follows: Jayanthi, G. and Uma, V. (2017) 'A qualitative inference method for prediction of geographic process using spatial and temporal relations', *Int. J. Artificial Intelligence and Soft Computing*, Vol. 6, No. 1, pp.1–23.

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1 Introduction

Knowledge representation (KR), a discipline under artificial intelligence prominently establishes logical computation for automated reasoning. The task of this information processing involves pre-processing of data and codifying facts to infer knowledge collectively termed as representation of knowledge about real world (Allen and Ferguson, 1994; Chittaro and Montanari, 2000; Pani and Bhattacharjee, 2001). The importance of knowledge representation is realised with codified knowledge that utilises mathematical logic in the form of simple declarative statements termed as propositional logic. The expressiveness is enhanced by using first order predicates. Both involve logic computation, but they differ in the way of using variables, quantifiers and operators. The outcome of knowledge representation is a knowledge-base that forms source of inference in solving complex tasks. The need for knowledge-based systems, intelligent agents design and cognitive systems have directed many prospective researches in this domain (Cohn et al., 1997; Bennet, 1997; Li, 2006; Li and Cohn, 2009).

KR is concerned with symbolic representation of real world data for automated reasoning in many real time applications in the field of cognitive sciences, natural language processing, planning, prediction and explanation by observation (Freksa, 1991; Frank, 1991, 1992, 1996; Allen and Ferguson, 1994).

1.1 Why knowledge representation is required?

Real world facts are imprecise, uncertain, fuzzy, missing, inconsistent, incomplete and dynamic. Set of disciplined activities that transform raw facts are necessary to infer knowledge. In general, spatio-temporal datasets are voluminous and involve massive computations. Although relational query processing over these datasets acquires quantitative results that are substantial for knowledge discovery with database technology, qualitative analysis of complex geo-spatial process incurring spatial dynamics that aids in study of geomorphology is a highly demanded add-on service to be rendered by database technologies (Cohn et al., 1997). Therefore it is essential to explore the directions shown by various researchers towards qualitative knowledge representation techniques to resolve the purpose of this work. Hence, this work aims at investigating knowledge-based geographic information system (GIS) dealing with spatial dynamics by considering their temporal attributes.

1.2 What is qualitative reasoning?

In the perspective of knowledge representation and reasoning (KRR) spatial entities are considered to be qualitative in nature. Unlike quantitative methods, in which numerical calculation is involved with the amount of accuracy and preciseness, comparison of spatial scene captured by human sensory vision is qualitative in nature (Freksa, 1991; Cui et al., 1993; Cohn et al., 1997).

Every real world scenario includes space as a dimension. Hence, geospatial entities occupy space irrespective of their size, shape and volume. Qualitative analysis of these spatial data yields comprehensive solution to many problem solving approaches. For instance, to answer the query, when and where did the earthquake happen? The precise and accurate measure of time is not of interest rather the answer would list those events that happened before and after earthquake and the spatial objects that were closer to the region of interest. The application areas where qualitative reasoning is well applied are geographical information system, Cognitive systems and natural language processing (Cohn et al., 1997; Muller, 1998a, 1998b; Nanni et al., 2004; Pani and Bhattacharjee, 2001).

1.3 Temporal reasoning

Given a situation, the mechanism by which an intelligent system best describes an event, effect of its occurrences and its relation with successive events as they evolve is temporal reasoning. Temporal reasoning is crucial and plays a major role in the development of cognitive systems, plan recognition, robot navigation, agent technology and other areas of computer science involving data modelling and information processing (Pani and Bhattacharjee, 2001).

1.4 Spatial reasoning

Given an object in space, the mechanism through which an intelligent system visualises the object that is navigating in a scene irrespective of its size, shape, volume etc., is inferring spatial interaction of a navigating object. This phenomena best describes the interaction of objects within a boundary and extending boundary. It plays a wider role in artificial intelligence with prominent applications in geographical information systems, robot navigation etc. (Egenhofer and Franzosa, 1991; Randell et al., 1992; Cui et al., 1993; Cohn et al., 1997).

1.5 Spatio-temporal reasoning

Spatio-temporal reasoning is the ability of the system to provide spatial and temporal description of objects in a scene. In the context of GIS, universe is diverse in nature with variety of geographic features, species, habitats which tend to change over a period of time. Physical geographic features were found to exhibit difference in their morphology over time. Consequently, such an effect causes spatial features to evolve which could well describe a geographic phenomenon that have occurred over the time period. Hence, abstraction of these aspects in real world into an automated reasoning system empowers human decision in most of the geographic applications (Muller, 2002; Galton, 2004; Galton and Worboys, 2005; Worboys, 2005).

The various researches towards theory of space, time and space-time together and their directions in reasoning geographic processes with temporal descriptions are explored in this work. Finally, logical formulation of geographic event attributed spatial entity (GEASE) knowledge-base to infer events that cause geographic process is proposed.

This paper is organised as follows: Section 2 elaborates various KRR approaches from literature. Section 3 describes the related works in inferring geographic events and processes. Section 4 introduces formal representation of GEASE knowledge-base. Section 5 discusses on event based queries and the results obtained and finally, Section 6 concludes with a summary and direction to future work.

2 Literature review

Theory of space and time is of prime importance to process spatio-temporal dataset. This section explores the representation and reasoning techniques from literature that laid foundation for the evolution of geographical information systems. The various approaches to qualitative knowledge representation and reasoning (QKRR) and their conceptual aspects that have been argued and adopted by researchers to ease activities involved in information processing pertaining to GIS are discussed. The importance of QKRR in the domain of spatio-temporal GIS would be well appreciated by exploring temporal aspects, spatial aspects and spatio-temporal aspects individually. At the end of this section we enumerate the prospective research direction.

2.1 Temporal knowledge representation and reasoning (TKRR)

Computation of time is an essential process involved in problem solving approaches of artificial intelligence such as cognitive planning, prediction and explanation from observation (Allen and Ferguson, 1994). Table 1 describes the significant approaches considering temporal knowledge representation. Representation of temporal facts finds its origin by defining a point on a time line (Khan and Gorry, 1977). In addition to reasoning about present time instances, its continuity in future is highly demanding. The need for expressive representation of temporal logic and various approaches to natural language processing necessitated the requirement of preciseness over intervals on a timeline (Allen, 1981).

The importance of point and interval representation of temporal facts was well appreciated by interrelating point and interval in reasoning about absolute date (Vilain, 1982). Further, the significance of hierarchical temporal relation propagating between intervals is formulated as temporal logic network (Allen, 1983). Though problem solving on temporal intervals is adequate, there is a lack of representation for many real world scenarios as they rely on actions with no activity (e.g., the cat is sitting on a chair). Each action has subdivisions in which one action links another and some actions occur simultaneously with interactions (Allen, 1984).

In the perspective of problem solving approaches in AI, valuable efforts are taken by researchers towards imprecise and incomplete temporal knowledge. Generalisation of Allen (1981) on interval-based approach led to investigation on reasoning missing information to solve the issue on uncertainty of events at end points (Freksa, 1992). The emerging trends of KR approaches towards deductive databases, GISs and plan reasoning have shown interest in formalising events and processes with partitioned temporal locations, where exactness is not guaranteed and hence reasoning a partitioned temporal location is approximate (Bittner, 2002).

Shanahan (1999) proposed an extension to event calculus (Kowalski and Sergot, 1986) so as to extend the expressiveness of situation (state) and actions to be performed in that state in terms of reasoning events, which is a static view of the universe. New predicates and axioms were introduced as extensions for reasoning events whose actions have an indirect effect. This approach solved the issue of reasoning by predicate completion. Logic programs were developed to show their application on events involving concurrent actions. This extended event calculus with minimal predicate has been analysed for events that show continuous change, non-deterministic event types and an interpretation of compound action that leads to consequent action.

Table 1 Qualitative temporal knowledge representation and reasoning methods

Approaches to TKRR	
Method	*Concept and significance*
Interval logic (Allen, 1981)	• Point and interval are temporal components. • Defines relation between time intervals for reasoning about events with temporal description.
Semi interval logic (Freksa, 1992)	• Involves point and interval as temporal entities. • Allows vagueness in endpoints.
Approximate temporal reasoning (Bittner, 2002)	• Involves granular temporal entities such as time, day, hours, minutes, seconds. • Reasoning relations between events and processes on an approximate partitioned time line.
Temporal granularity and indeterminacy event calculus (TGIC) (Chittaro and Combi, 2002)	• *Happens* clause based on event and time point. • *Initiates and terminate* clause based on event and property. • An approach to overcome issues with imprecise temporal data in event calculus with solution obtained in linear time. • Reasoning events that are not precisely determined in different time scales.
Geospatial event model (GEM) (Worboys and Hornsby, 2004)	• An UML extension in which events and objects are different entities describing dynamic aspect of geo-spatial processes. • Basic foundation for event based querying of dynamic scenarios.
Versatile event logic (Bennett and Galton, 2004)	• A semantic-based formalism of spatio-temporal entity considering both situation calculus and event calculus.

The issue of reasoning imprecise temporal data to handle events that are not precisely determined at different time scales was solved by proposing a formal method TGIC by introducing new clauses namely *happens* based on event and time, *initiates and terminates* based on event and property in addition to the predicates in the event calculus approach (Chittaro and Combi, 2002).

Worboys and Hornsby (2004) proposed an object-oriented event model GEM as an extension to unified modelling language (UML). In this approach, a geospatial object is distinguished from the geospatial event. Further, it is extended for describing the dynamic aspect of the geospatial system in order to support event-based query languages by describing object to event and conversely event to object relations.

The profound theory of time and its constituents such as points, interval, events, processes and action in domain of geospatial dynamics have led researchers to innovate event model for information system design wherein temporal, spatial and spatio-temporal events and their relations are classified using object based paradigm that bridges the gap between conventional spatial data models and spatio-temporal object model (Bennett and Galton, 2004).

2.2 Spatial knowledge representation and reasoning (SKRR)

A geographic spatial extent captures possible interrelations between various physical geographic features. Hence, formalising such spatial relations has laid foundation for evolution of geo-spatial reasoning systems. This section covers various concepts in spatial representation methods within the literature and their use in geographic applications. Amongst various approaches to knowledge representation and reasoning in spatial domain the significant methods are explained in Table 2 to appreciate the need and their importance in geographic applications.

Table 2 Qualitative spatial knowledge representation and reasoning methods

Approaches to SKRR	
Method	*Concept and significance*
Abstraction of space (Whitehead, 1929)	• Predicates are defined to show abstraction of physical object in space. • It is a primitive formalism to define physical existence, but cannot define other spatial relations.
Calculus of individuals (Clarke 1981, 1985)	• Based on concept of mereology – parts and wholes. • Involves Boolean operations and topological operators such as interiors, exteriors etc. • Reasoning individuals on parts and wholes.
Point-set topology (Egenhofer, 1991)	• A point set topology spatial relation defines closed sets and open sets with condition on union and intersection. • Distinguishes overlap and neighbour by reasoning *interior* and *boundary* of regions.
Region connection calculus (RCC-8) (Randell et al., 1992)	• Eight disjoint boundary sensitive topological relations. • Reasoning region splits and boundaries.
9-intersection calculus (Egenhofer et al., 1994a, 1994b)	• Binary topological relations defined between two spatial objects in terms of *interiors, boundary and exteriors* using intersection.
Boolean connection algebra (BRCC) (Stell, 2000, 2004)	• An equivalent model of RCC-8. • Boolean connections equivalent to RCC was proved for spatial relations such as *part of, proper part, overlap, externally connected and non-tangential proper part*. • Notion of complement was introduced to connected relation C_{xy} in RCC.
RCC-8c and RCC-8c (Kontchakov et al., 2014)	• Involves eight topology relations and its compositions. • Reasoning connected region and connected interiors.

The need for inference engine to understand the characteristic features of space has found its origin with Whitehead's two place predicate. It is an abstract representation of physical objects. This primitive representation of space could not solve the problem of representing spatial objects and their relations. Following this primitive formalism, Clark refined the latter using concept of mereology, the relation defined between parts and wholes. A number of algebraic relations were sought (Clarke, 1981, 1985). This theory laid foundation for many spatial models dealing with an individual object but did not solve the topological issues within spatial domain. This was overcome by Egenhofer's (1991) theory, in which formalising topological relations was given importance (Egenhofer and Franzosa, 1991).

Mathematical foundation to topological relations was laid by defining algebraic formulae, rules and axioms over binary topological relations describing object boundaries and interiors (Egenhofer and Franzosa, 1991). Using principles of set inclusion and transitivity axioms, intersecting objects were interpreted. In this way, eight fundamental topological relations were deduced leading to the composition of topological relations (Egenhofer, 1991). Of special interest, to address issues in spatial reasoning pertaining to geography, Randell et al. (1992) evaluated the original theories of Clarke (1981) and Egenhofer and Franzosa (1991) by making comparison with minimal axioms, definitions and formulae as a description of interval logic. This led to the theory of region connection calculus (RCC). Few relations were introduced that are syntactically meaningful and that provides better expressiveness. In addition to topological information, importance of reasoning space with direction and motion of objects based on interval logic was discussed (Frank, 1991, 1996; Navarrete and Sciavicco, 2006; Morales et al., 2007; Salamat and Zahzah, 2011). The expressiveness of topological relations that are defined as point set by Egenhofer and Franzosa (1991) was improved with extensive axioms to reason the orientation of spatial object (Cui et al., 1993). Eventually, this approach has enabled the formal representation of regions that have holes protruding inside and that move out of boundaries (Egenhofer et al., 1994).

Bennett (1994) investigated the issues behind expressiveness of first order predicate logic and computational complexity. With available compositional table and axioms (Li and Ying, 2003, 2004), the simplicity of representation on spatial relations using propositional logic was formulated for automated theorem proving. In order to realise consistent spatial network with eight base relations of RCC, formal algorithm was proposed. However, complexity of the algorithm remains unsolved.

Cohn (1995) has shown a primitive method with distinguishable qualitative shapes in theory of space and their connectivity using connectedness and concavity was proposed. Apart from applying representation and reasoning approaches to knowledge of space, many works were carried out towards analysis of algorithmic time complexity over region connections. It was found that the complexity of spatial reasoning is NP-complete (Renz and Nebel, 1999). Nevertheless, algebra of binary topological relations has been extensively analysed for better expressiveness by mathematically proving the properties (Duentsch, 2005). Egenhofer et al. (1994) stated that geometric objects and their relationships are key components for spatial data analysis. Further, nine different binary relations are well-defined using the topological operators *interior, exterior and boundary* by finding intersections between two spatial regions, lines and points.

Stell (2000) proposed BRCC and proved it to be equivalent to RCC. The need of Boolean connection was raised due to the difference in mereo-topology and topology of region connections. Boolean algebra when applied to region and its connections distinguishes the concept of mereology and spatial topology relations. Methods that are extension to Boolean region and connections were described. Despite the increase in computational complexity, reasoning with directional relations is found to be necessary to enhance tableaux-based deduction systems (Morales et al., 2007). Hierarchical structure for topological relations was derived from RCC-8 relations (Randell et al., 1992) to resolve cartographic issues using knowledge representation through lattices to meet specific geographic application (Napoli and Le Ber, 2007). A minimal composition table was deduced by comparing Allen (1981) 13 relations to sufficiently build transitivity graph for temporal and spatial logical computations (Cohn et al., 1994). A set of points and its connections taken together as a region formulated as RCC with eight topological relations was extended as RCC-8c denoting region connectedness. RCC-8c^o was proposed to define regions that have connected interiors (Kontchakov et al., 2014).

2.3 Spatio-temporal knowledge representation and reasoning (STKRR)

Logical framework for spatial continuity over time has evolved and its computational complexity was explored. From existing theory of RCC, Allen's (1981) interval logic and composition table, transition graphs are derived and analysed on basis of structure which has led to the concept of conceptual neighbourhood in reasoning about space and time (Gooday and Cohn, 1994; Wolter and Zakharyaschev, 1999; Bennett et al., 2002; Stell and Worboys, 2008; Galton, 2009).

Situation calculus uses axioms formulated by first order logic to describe the real world, whereas event calculus is bounded by events and time periods. Further, this feature of event calculus approach was experimented in situation calculus by formalising facts in clausal form to resolve using resolution with refutation. Thus, a logic based approach for computation of events was developed. This was extensively applied in the update of conventional database where new knowledge is added without explicitly deleting the past records (Kowalski and Sergot, 1986). In hierarchy of spatial relations, inferring topology of region was formulated using the notion of inclusion. This has shown path to deduce additional parameters such as distance, geometry and orientation in reasoning motion of spatial object (Cohn, 1995; Muller, 1998a, 1998b). In this view, qualitative reasoning of spatial topology in space-time history is promising.

The separate theory of space and time is rather not addressing the issues pertaining to physical geographic features and their combined approaches have not shown formal deductions (Muller, 2002). Hence, theory of space-time is not approached separately as spatial and temporal components are treated uniformly in problem-solving approaches. Thus, Randell et al. (1992) region and its connections and Allen (1984) interval calculus have supported the theory of space and time respectively. Structural properties are then defined using the concept of parts and wholes (Clarke, 1985).

Claramunt and Theriault (1996) stated that entities are outlined through spatio-temporal processes and their prospective relationships involve processes between many entities. In this view geographic phenomenon evolving over time was modelled using event pattern language (EPL). The syntax and rules thus proposed have modelled complex spatial processes that have found its application in semantics processing of temporal GIS applications. The scope of influence on the variety of geography phenomena can be viewed both as object and process (Galton, 2003). For example, consider landslide in the hilly region and oil slick in the sea. They both describe a process as well as an object undergoing phenomenal change. In this perspective, the need for geo-ontology comprising field-based view and object-based view as a form of representation of world was stated.

The importance of space-time theory in KRR can be well understood by exploring specific work to relate logics with spatio-temporal data. This will lead to explicit specification of spatial entities by defining an ontology in which, dependent entities are further categorised without affecting its logical interpretations. For example, colour, size and shape of a feature describes spatial parts whereas, transformation of feature into another kind is not part of it rather it denotes a process (Galton, 2004). Hence, their dependencies are to be differentiated. Though both categories are attributes of a spatial entity their dependencies are to be resolved to infer its endurance and perdurance. Thus, field based view and object-based view of identifying events and processes in space-time histories of object are found to exhibit endurance and perdurant behaviours (Grenon and Smith, 2004).

Process oriented dynamic geospatial system was modelled. A generic ontology was formulated to describe the static and dynamic aspects of spatio-temporal GIS data analytics and geographic phenomena (Galton and Worboys, 2005). Formalism denoting the fundamental ontological distinction between experience and history was stated. The underlying principles such as events form fixed items of history, whereas processes that can undergo change as time proceeds from ordinary object was stated (Galton, 2008). Event-oriented approaches have significant impact towards the conceptual modelling of spatial phenomenal change. Most of the authors have focused representation of geographic features evolving over time rather than representing its motion through a region (Worboys, 2005).

Of special interest in conceptualising object-oriented approaches in manipulating and querying spatio-temporal data, a definition based ontological framework was presented (Campelo et al., 2012). Although most of the theoretical formulation of spatial change applies to spatial extension of geographic feature, they are yet to show comprehensive results when experimented on real datasets (Galton, 2008; Stell and Worboys, 2008). This has necessitated modelling spatio-temporal data to identify events and process. Recent researchers have found that spatial change over time also result in attribute changes that are aspatial (colour, size, type etc.). Subsequently, based on theory of region connection and interval calculus, logical framework was derived to identify events and processes that have occurred. Process is that proceed due to phenomenal change (event) in geographic features and their extensions over time (Campelo et al., 2011, 2013).

Modelling dynamic characteristics of geographic features embodies the events and processes that are undergone by spatial entities. GIS applications can be developed using geo-ontology to perform analysis of geographic phenomena by querying spatio-temporal database. In some situations, human intent to interpret geographic phenomena as processes happening in time series. Spatial regions exhibit different behaviour at different time. For instance, dense homogenous feature type of a region at one time in dynamic space may be heterogeneous coverage type or a simple feature type at another time. Thus, to handle such phenomena spatio-temporal data model STAR was proposed (Campelo et al., 2011, 2013).

Although KRR approaches have shown flexibility in handling dynamic characteristics, geographic processes like region aggregation; region split in various temporal granularities etc., tend to be vague and the categorisation issue related to spatial and temporal information granularity remains unsolved. Thus, the work explored with regard to KRR has shown evidences on how spatial extension over time evolved and its continuity. However, temporal attributes like point, interval and events have not been qualitatively analysed on extending space. Rather, they have been analysed on space over consecutive time periods thereby inferring space-time history (Cohn et al., 1997; Hazarika and Cohn, 2001; Hazarika, 2005). Table 3 explains the various knowledge representation approaches to spatio-temporal data.

Table 3 Qualitative spatio-temporal knowledge representation and reasoning methods

Approaches to STKRR in GIS		
Method		*Concept and significance*
Theory	Event-oriented (Claramunt and Theriault, 1995)	• Topological framework for representing entity based events and processes. • Evolution of spatial entities and their relationship with respect to spatio-temporal processes.
	Mereo-topology (Muller, 1998a, 1998b)	• Qualitative framework involving theory of spatio-temporal entities. • Describes motion of spatial entities.
Calculus	EPL (Claramunt and Theriault, 1996)	• Taxonomy of spatio-temporal processes.
	Versatile event logic (Galton, 2004)	• Combination of situation calculus and Event calculus. • Representation of time and events as general temporal ontology.
Space-time ontology	Spatio-temporal geo-ontology (Galton, 2003)	• Spatial objects are continuants. • Interconnections between field based and object based view. • Describes spatio-temporal phenomena such as storms, floods and wildfires.
	SNAP and SPAN (Grenon and Smith, 2004)	• Spatial ontology representing snapshot views of the world at successive instants of time. • Spatio-temporal ontology representing change and process termed as endurant and perdurant behaviours of spatial feature respectively. • Spatial dynamics describing geographic features in space and space-time.
	Processes and events (Galton and Worboys, 2005)	• Generic ontology represented using dynamic geographic phenomena in form of a graph. • Specific application found in spatio-temporal GIS for information extraction.
	EXP and HIST (Galton, 2008)	• EXP describes processes existing at one time; HIST represents history recorded with events generated by processes. • A singleton time predicate to code EXP. • Time varying predicate to code HIST.
	DOLCE (Devaraju and Kuhn, 2010)	• Process centric ontology defined by identifying processes, entities and physical properties. • Ontology distinguishes one process from other processes via participation relations. • Categorises hydrological processes and its entities.

Table 3 Qualitative spatio-temporal knowledge representation and reasoning methods (continued)

Approaches to STKRR in GIS		
Method		*Concept and significance*
Spatio-temporal data model	Reasoning about geographic processes (RGP) (Campelo et al., 2011)	• Spatio-temporal data formulation to model spatial and temporal attributes to relate occurrence of events to geographical processes. • Reasoning evolving homogenous and heterogeneous geographical feature type over time.
	Reasoning about geographic events and processes (REGEP) (Campelo et al., 2012, 2013)	• Knowledge representation approach to identify geographic feature type based on events and processes in temporal series of topographic data. • Reasoning geographic processes.

Towards inferring geographic spatial entities, most of the works deal with spatial extensions and its continuity over a period of time. When analysing events to infer spatial dynamism causing spatial extension due to geographic process, there is a need for spatio-temporal relation based representation. Event calculus approach supported by interval logic was considered to define process change on time line as temporal entity whose attributes are point and interval that together form a qualitative representation of time. RCC-8 with eight topological relations is adapted to model geo-spatial entity describing phenomenal change over an instant of time. This way formalism of GEASE knowledge-base is proposed in this work. This knowledge-base when queried will aid in reasoning events causing geographic process.

3 Related work

The motivation behind this work is to investigate KR approaches to infer events and its characteristics on changing geographic features. Table 4 describes the conventional KRR languages viz. situation calculus (SC) and event calculus (EC).

The event occurrence on timeline describes a spatial entity and this is considered as region of space that undergoes geo-spatial change or geo-spatial region extension due to external phenomena denoting a geographic process. The related work that has been carried out in this direction of research is explored in this section to show in what way the proposed system is different from other approaches in problem solving.

The abstraction of real world started with the theory (Clarke, 1981, 1985) of mere topology – parts and wholes followed by region and connection (Randell et al., 1992), point sets and topology (Egenhofer and Franzosa, 1991; Egenhofer et al., 1994). The Allen (1981, 1983) interval logic has paved the way to formalise event calculus, a logical language to describe events and actions. In contrast to situation calculus, Event calculus approach has handled physical geographic data whose characteristics vary in spatial extension with respect to time irrespective of its exhibitive physical geographic phenomena such as location, geometry in shape, size, direction and orientation (Shanahan, 1999). In the perspective of space-time continuity in GISs, Hornsby and Egenhofer (2000) proposed a significant model to identify a changing physical object. The phenomenal change exhibited by the object could be a land cover appearing as vegetation in the past may appear as built up area in the present. However the exact event that has caused this phenomenal change is not of interest in the study and this laid foundation to many spatio-temporal data analysis.

Table 4 Logical reasoning languages

Conventional knowledge representation and reasoning languages		
Logical language	*Situation calculus (McCarthy and Hayes, 1969)*	*Event calculus (Kowalski and Sergot,1986)*
Concept	• Defines fluent in form of states and actions.	• Defines fluent in form of events and actions.
Significance	• Describes snapshots of situation as states of universe and sequence of actions to be performed. • Extract of action plan from states to reach goal.	• Defines value of fluent with action and effect of action at an instant of time. • Clausal form of representation deduced using resolution by refutation and it is effective when applied to update records without losing past records in conventional databases.
Comparison	• Branching time representation: Sequence of situations is not contiguous, where an action in current situation has no relation with action happened in past. • Duration of action cannot be analysed.	• Linear time representation: each event has unique time line. • A segment of time could define relation between two events.

Every spatial object has abstract view of identity whose spatial extent would be definable at any moment. This led to a conclusion that temporal parts do not have any effect over identity of physical geographic characteristics of a spatio-temporal entity. Thus spatial objects exhibit endurance and perdurant behaviour (Galton, 2003).

From philosophical point of view, the following terms describe its use in spatio-temporal ontology.

- *Continuant* – describes the state of existence of a spatial object in spite of change in the state of behaviour and its relation to other states. For example, geographic features that evolves over a time period.
- *Occurrent* – describes existence of a spatial object in order to explicitly describe the phenomenon caused by changing states. For example, deformation of land parcels over a time period.

The importance of modelling spatio-temporal interactions and their relations changing over a period of time was analysed. Temporal attributes were introduced to define spatial interactions with respect to time. Consequently, Muller (1998) formulated a theory that has paved way for expressing continuity of space over time. Most of the work was directed towards semantic formalism in addition to conceptualisation of space-time theory. In this view, Claramunt and Theriault (1996) proposed semantic formalism based on EPL. Galton (2003) proposed geo-ontology framework to formalise individual spatial objects for continuants and chunks of events for occurrence thus describing events, processes and their change. The ground truth value is field data and the spatial individuals affected by change are object based view of the space. Thus, the relationship between object based view and field based view shows that a physical geographic feature of a field data could be designated as object. An individual object can further derive different fields describing its kind. Unlike spatial objects, fields do not have the issue of identity. In modelling geographical processes, Devaraju and Kuhn (2010) presented space-time interactions between processes and its participants in terms of physical and chemical properties.

Table 5 Spatio-temporal entities involved in spatial dynamics

Knowledge representation and reasoning in spatio-temporal GIS							
		Temporal entities		*Spatial entities*			*Spatial dynamics*
		Instantaneous point	*Interval*	*Point*	*Region*	*Region kind*	
Logical languages	Situation calculus (SC) (McCarthy and Hayes, 1969)	✓	≅	≅	C	T	T^+
	Event calculus (EC) (Kowalski and Sergot, 1986)	✓	✓	✓	C, IC	T	T^+
	Event pattern (Claramunt and Theriault, 1996)	✓	✓	✓	C, IC	T	T^+
	Versatile event logic (Galton, 2004)	✓	✓	✓	C, IC	T	GP, T^+
Space-time ontology	Spatio-temporal geo ontology (Galton, 2003)	✓	✓	≅	C, IC	T, G	G^+, T^+
	SNAP and SPAN (Grenon and Smith, 2004)	✓	✓	≅	C, IC	T	G^+, T^+
	Processes and events (Galton and Worboy, 2005)	✓	✓	≅	C, IC	T	G^+, T^+
	EXP and HIST (Galton, 2008)	✓	✓	≅	C, IC	T	G^+, T^+
	DOLCE (Devaraju and Kuhn, 2010)	✓	✓	≅	C, IC	T	G^+, T^+
Spatio-temporal data model	RGP (reasoning about geographic processes) (Campelo et al., 2011)	✓	✓	✓	C,IC	T	GP
	STAR (spatial temporal attributed regions) (Campelo et al., 2012, 2013)	✓	✓	✓	C,IC	T	G^+, GP, T^+
	*GEASE knowledge-base	✓	✓	✓	C, IC	T	G^{++}, GP, T^+

Notes: *Proposed qualitative spatio-temporal representation and reasoning.
Legend: Region: (C) connected; (IC) interconnected;
Region kind: (T) topological; (G) geometrical;
Entities: (✓) proved; (≅) exist;
Spatial dynamics: (G^+) geographic; (G^{++}) geomorphology; (T^+) topography; (GP) geographic process.

This was further enhanced by the way of modelling spatio-temporal data (STAR) (Campelo, 2012, 2013). The proposal on identification of events and processes from time stamped data STAR model was put forth and it was stated that geographic regions are governed by spatial and temporal attributes. Further, spatial attribute identify a specific coverage of a feature type categorised as homogenous, heterogeneous and simple coverage (Campelo et al., 2011). The most accepted view amongst various authors is that, events are not bounded by time. Events are perdurant entities, that have temporal parts and process is an entity that is subject to undergo change over time (Galton, 2004; Grenon and Smith, 2004). The goal of investigating representation of real world entities whose typical features are embedded within space and time is to reason events that cause spatial change of a physical geographic feature. It can be expressed that, spatial attributes on geographic region describe feature types such as land coverage, shape, size, colour etc., with respect to time and temporal attribute of a spatial region of specific feature type describes an event. Hence, an event in a geographic region is the cause for the occurrence of change in the feature types such as colour, shape and size.

The phenomenal change that has led to this situation would describe the events that are the reasons for change. In this work, spatial and temporal relations are used to formulate GEASE knowledge-base for qualitative spatial entity reasoning, in which a geographic region is describing a physical geographic feature with temporal description of events as attribute. The eight spatial relations of RCC are considered to assert spatial entities and Event calculus is applied in reasoning events (spatial change) that cause the change in geographic feature due to geographic phenomena. The chunks of events between the start and end of a spatial change will describe the spatial process through which the geographic feature has evolved over the period of time. Table 5 shows the effect of spatial and temporal entity participants in describing spatial dynamics.

4 Formulation of GEASE knowledge

4.1 Formal representation

The formal representation of real world facts about space, time and the rules for interpreting the facts in the domain of GIS are considered for the logical formulation of GEASE knowledge-base. The objective of GEASE is to infer events acting on the geographic region of interest at different temporal scales, thereby causing geographic process.

In this perspective, spatio-temporal dataset describing universal facts such as land cover change, deformation, and extension of boundary etc., about a geographic region at different time period is modelled with temporally attributed spatial entities. The Geographic process prediction model is defined by five components ($\mathfrak{R}$, T, τ, E, S_p) where, $\mathfrak{R}$ denotes geo-spatial region; T denotes time; τ denotes time-instance; E denotes event; S_p denotes spatial process. Each of these components is represented and defined as follows.

Definition 1: Spatial region $\mathfrak{R}$. Spatial region $\mathfrak{R}$ is defined as a finite set $\{r_1, r_2,.,.,r_n,\}$ where r_i denotes a polygon describing a sub region such that $r_i \in \mathfrak{R} \in \mathbb{Z}^+$, denotes the sub regions in $\mathfrak{R}$ and $n \in \mathbb{Z}^+$, denotes the number of sub regions in $\mathfrak{R}$.

$$\Re \equiv {}_{def}\{r_i \mid \text{where } r_i \in \Re \text{ for } 1 \le i \le n, \text{ otherwise } \varnothing. \quad (1)$$

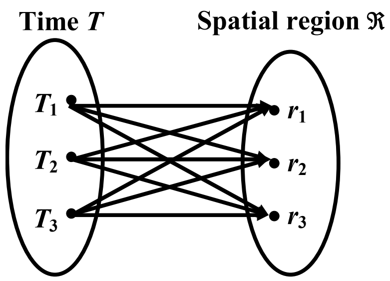
r_i is a connected region as described by the axiom C_{xy} in RCC (Randell et al., 1992).

Definition 2: Time T. Time T is defined as a finite set $\{T_1, T_2,.,.,T_m\}$ where T_j describes spatial region $\Re$ at time instance 'j' and $1...m$ denotes period for which the region $\Re$ is monitored.

$$T \equiv {}_{def}\{T_j \mid \text{for } 1 \le j \le m, \text{ such that } \forall r_i \text{ in } \Re, \exists T_j. \quad (2)\backslash$$

Hence $\{T\}$ is not null for any sub region in $\Re$. This can be further explained by mapping the relation between T and $\Re$. Thus, the mapping shown in Figure 1 describes the event spatial change occurring in sub regions r_1, r_2, r_3 at T_1, T_2 ,T_3.

Figure 1 Spatial change at T in spatial region $\Re$



Definition 3: Time instance τ. Time instance τ is defined as a finite set of instances $\{\tau_1, \tau_2,.,.,\tau_q\}$ such that the temporal granule of T_j is represented by τ_k.

$$\tau \equiv {}_{def}\{\tau_k, \tau_k \in \tau \in T_j \mid \text{for } 1 \le k \le q, q \in Z \quad (3)$$

such that $\tau \ne \varnothing$ as $\sum_{k=1}^{k=m} \tau_k = T_j$, where $\tau_2 - \tau_1 = \tau_3 - \tau_2 = \ldots\ldots = \tau_m - \tau_{m-1}$.

Definition 4: Event E. Event E is defined as spatial change occurring in sub region r_i, $r_j \in \Re$ at time instance τ_k such that

$$E_{ijk} \equiv {}_{def}\{P(r_i, r_j), \tau_k \mid \text{where } r_i, r_j \in \Re \text{ and } \tau_k \in \tau \quad (4)$$

P is a set that denotes topological relations as defined in RCC such that $P \in \{PP_{xy}, P_{xy}, O_{xy}, EC_{xy}, DC_{xy}, DR_{xy}\}$ where PP_{xy} is 'x proper part of y', P_{xy} is 'x is part of y'; O_{xy} is 'x overlaps y', EC_{xy} is 'x externally connected with y', DC_{xy} is 'x disconnected y', DR_{xy} is 'x is discrete with y' where x, y denotes sub-regions r_i, r_j respectively.

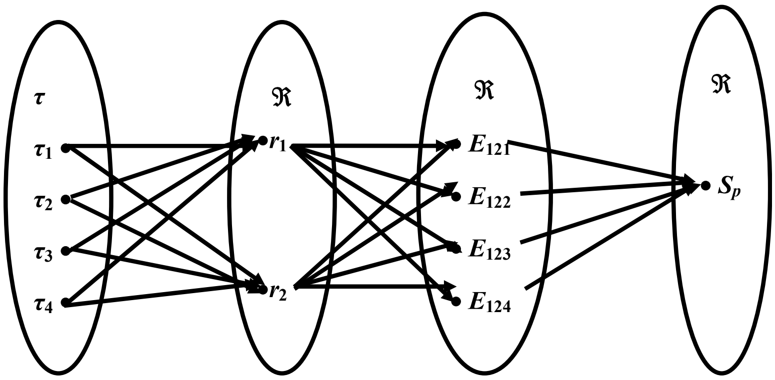
Definition 5: Spatial process S_p. Spatial process S_p is defined as consecutive occurrence of spatial change event E_{ijk}, E_{ijl} in r_i, r_j at different temporal granules τ_k, $\tau_l \in \tau$ such that,

$$E_{ijk} \ne E_{ijl} \text{ where } \tau_k < \tau_l, \tau_k, \tau_l \in \tau \text{ and } r_i, r_j \in \Re. \quad (5)$$

< denotes Allen's (1981) temporal relation *before*. Thus, as shown in Figure 2, S_p is implied when $E_{ijk} \ne E_{ijl}$. The sequence of events E_{ijk} participating in sub regions of $\Re$ together constitute a spatial process occurred in $\Re$. This can be inferred from the domain

knowledge about geographic events causing phenomenal change in a geographic region over a time period.

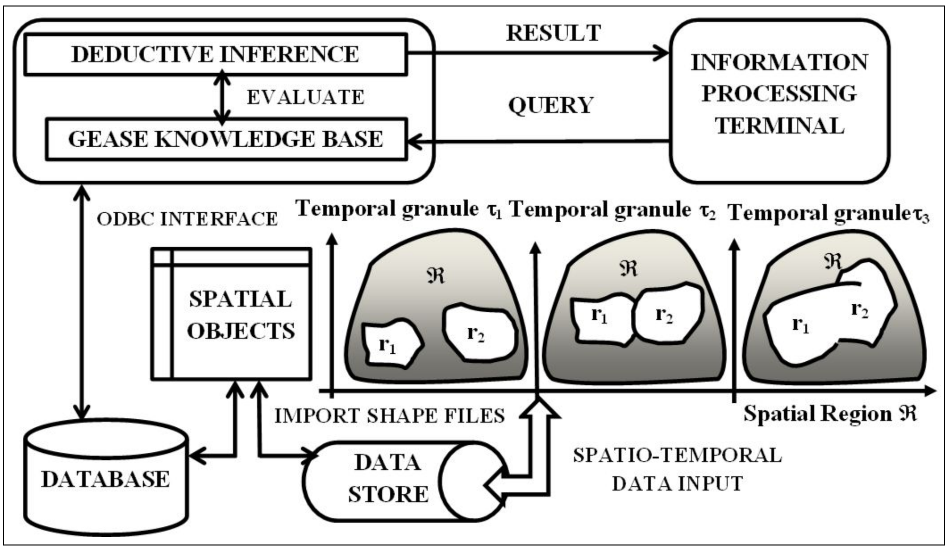
Figure 2 Mapping between events occurring at temporal granules describing spatial process



4.2 System architecture

The organisation of formulated GEASE knowledge-base and its flow of execution are explained with the system architecture shown in Figure 3. The system architecture describes the functional components and their purpose to facilitate qualitative reasoning in analysis of spatial entities of a specific geographic region of interest owing to the formulation of GEASE knowledge-base. The system requires spatio-temporal datasets about a geographic region $\Re$ collected at regular temporal granules τ_j (months) of T (year) in series. The functional description of each component is detailed as follows.

Figure 3 GEASE system architecture



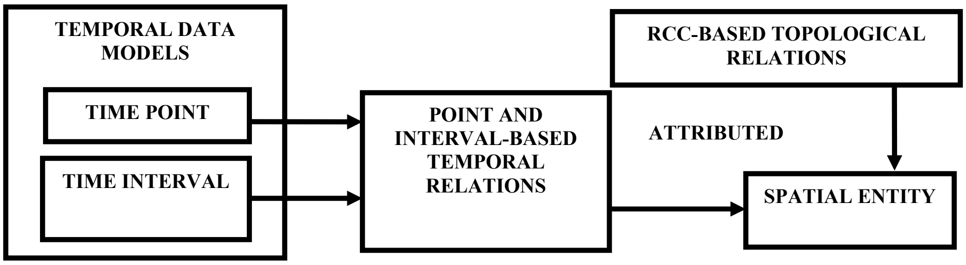
4.2.1 Spatio-temporal dataset

Topographic data in time series acquired using remote sensing technology in vector format is the source of input to the system. The spatio-temporal dataset whose physical geographic feature is to be analysed is loaded as shape file to data store.

4.2.2 GEASE knowledge-base

The facts about geographic regions are present in the data store. These facts are imported as spatial objects to a database over which the GEASE knowledge-base is to be formulated. Each sub region r_1 and r_2 in $\Re$ is a polygon denoting a spatial entity. The time instance τ is the temporal attribute of spatial entity describing an event E (spatial change). Thus, Allen's interval logic relations are used to codify the temporal attributes of spatial entity. Point, interval represent the time instant, period that describes the temporal activity of spatial entity. Temporal relations based on point, interval logic describe relation between events causing spatial change. These events are attributed with spatial entities that are in topological relations as defined by RCC. This is understood from logical view of spatial entities and temporal attributes shown in Figure 4.

Figure 4 Logical view of spatial entity with temporal attributes in GEASE knowledge-base



4.2.3 Spatio-temporal inference engine

The GEASE knowledge-base is built over the relational database to infer events acting upon the spatial entities of a geographic region $\Re$. Spatial and temporal deductive inference mechanism evaluates the user query by deducing the codified facts with inference rules in GEASE knowledge-base.

5 Query evaluation results

SWI-Prolog[1] is a program development tool which is freely available and distributed under Lesser GNU Public License (LGPL)[2]. SWI-Prolog 6.2.2 version[3] is installed and executed on a 32-bit, 2.1 GHz processor, 2GB RAM. A synthetic knowledge-base consisting of minimal facts and inference rules is created in SWI-Prolog. The source of input to GEASE knowledge-based system is spatio-temporal dataset in time series.

The eight topological relations defined by RCC and 13 temporal interval relations formulated by Allen (1981) are used to model spatial entity. Thus, the event causing geographic process in a region is detected by evaluating the following event-based queries Q1 through Q6 to express the significance of GEASE knowledge-base. The temporal granules τ_1 through τ_8 are the months of January through August of the year 2015 (T_j) respectively.

Q1 Did deforestation occur in sub-regions r_i and r_j of $\Re$ of during the month of August (τ_8) in 2015 (T_j)?

Result: This query would return *true* if deforestation was active at τ_8 in sub-regions r_i and r_j of $\Re$. The spatial entities are polygons denoting deforested sub-regions r_i and r_j of the geographic region of interest $\Re$. These polygons exhibit topological change due to deforestation at τ_8 thus describing a spatial change.

The geographic event acting on spatial entity is thus inferred. This query evaluation illustrates that temporal attribute identifies the geographic event that is occurring in sub-regions, which are the spatial entities existing in the geographic region of interest.

Q2 Was deforestation active in sub-regions r_i and r_j of $\Re$ between the months January (τ_1) and June (τ_6) in 2015 (T_j)?

Result: The spatial change events E_{ijk}, $1 \leq k \leq 6$ occurring in r_i and r_j at different temporal granules τ_1 through τ_6 of 2015 (T_j) are retrieved. On occurrence of event (deforestation), the topological relations in P holding between r_i and r_j will be changing at each temporal granule τ_1 through τ_6 of 2015 (T_j) such that $\tau_1 < \tau_2 < \tau_3 < \tau_4 < \tau_5 < \tau_6$, where < represents *before* temporal relation. Thus, geographic events occurring within a temporal interval are inferred.

Q3 What is the cause for land cover change in sub-regions r_i and r_j of $\Re$ in the month of June (τ_6) 2015 (T_j)?

Result:

1 The query would return *true* if spatial change leading to deformation is found in sub-regions r_i and r_j of $\Re$ before the time instance τ_6.

2 It returns the spatial process S_p that was implied by the events at different temporal granules of τ. Hence, it finally returns event E_{ijk}, E_{ijl} occurring at τ_k, τ_l in sub-regions $r_i, r_j \in \Re$ such that $E_{ijk} \neq E_{ijl}$. Thus, spatial process which is a land cover change is inferred at τ_6.

The temporal attribute identifies the geographic event due to which the land cover has deformed. Thus, a spatial process is inferred.

Q4 In the year 2015 (T_j) how long the spatial change E is persisting in $\Re$?

Result: This query would return temporal granules $\{\tau_1 \ldots\ldots \tau_6\}$ throughout which there exists spatial change such that $E_{ijk} \neq E_{ijl}$, where $\tau_k < \tau_l$.

Thus, temporal attribute describing the geographic events that are qualitatively persisting over a time period is inferred.

Q5 What events caused the earthquake in sub-regions r_i and r_j of $\Re$ in the year 2015 (T_j)?

Result:

1 The query return *true* if event causing earthquake S_p is detected in the year 2015 (T_j).

2 It returns all E_{ijk}'s in the order of temporal granule τ_k, defining the topological relations in *P* effected due to the spatial change events at temporal granules τ_k in the year 2015 (T_j).

This query evaluation shows how geographic events causing earthquake, spatial process in sub-regions are identified.

Q6 Are the sub-regions r_i and r_j of $\Re$ in year 2015 (T_j) susceptible to earthquake in future?

Result:

1 The query would return *true* when sub-regions r_i and r_j of $\Re$ are affected by spatial process in 2015 (T_j).

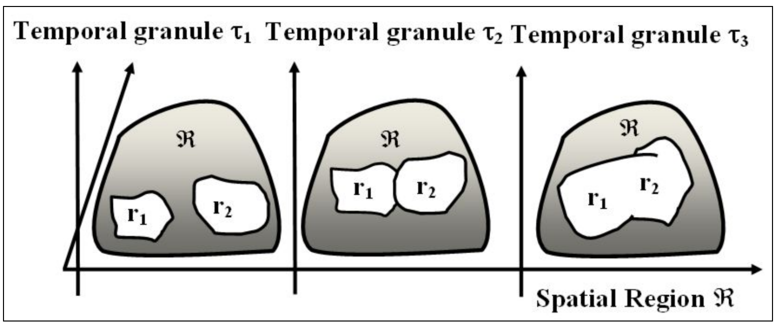
2 The system lists the spatial topology change that have effected or persisted in any of the months, which is the topological relations in *P* would be listed for all months of T_j.

3 The system returns all events E_{ijk}'s due to which the sub-regions have undergone accelerated deforestation. Thus, the spatial extent shown would describe accelerated deforestation in sub-regions r_i and r_j of $\Re$ at different temporal granules as shown in Figure 5.

4 When there is minimal or no spatial change in the sub-regions r_i and r_j of $\Re$ the system prompts the user that r_i and r_j are not susceptible to earthquake.

This query evaluation shows that by identifying geographic process occurrences qualitative prediction is possible.

Figure 5 Sub-regions r_1 and r_2 showing accelerated deforestation process



6 Conclusions

The objective of this work is to explore qualitative knowledge representation approaches to spatio-temporal GIS for reasoning physical geographic characteristics through spatial and temporal relations. The information processing using KRR faced the problem of representing the present state as a snapshot of universe. This method could not be applied to dynamic systems as concurrent actions and their interrelations cannot be identified. Hence, highly expressive representation is required in handling complex tasks. In this view, Event calculus approach based on Interval logic was found to be successful. The diverse application in spatio-temporal GIS has necessitated the investigation on KR approaches to physical geographic features such as space and time. Further, many semantic model and theoretical formalism have proved that the spatial and temporal aspects together yields satisfying solution to real time problem solving approaches. Though most of the research activities are supporting formalism of space-time theory in inferring spatial continuity and its extending spatial features over time, the issues of problem solving approaches in describing various qualitative characteristics of dynamic spatial entities remain unsolved. Such an issue targets on the requirement of a knowledge-based system that can infer qualitative characteristics of relative area affected by earthquake in successive periods. This knowledge-base aids in the prediction of geographic process such as earthquake, landslide etc., and also helps in identifying the events due to which the disasters have accelerated. Thus, GEASE knowledge-base is formulated to reason events that cause geographic processes constituting a phenomenal spatial change. The future work includes the experimentation of GEASE knowledge-base with real datasets.

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Notes

1 http://www.swi-prolog.org/Download.html.

2 http://www.swi-prolog.org/license.html.

3 http://www.swi-prolog.org/download/stable?show=all.