Toward Causally Aware GIS: Events as Cornerstones

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Abstract

Over the last 50 years, Geographic Information Systems (GIS) have become a vital tool for decision-making. Yet, the increasing volume and complexity of geographical data pose challenges for real-time integration and analysis. To address these, we suggest a causally aware GIS that represents causal relationships. This system uses causality to analyze events and geographical impacts, aiming to offer a more comprehensive understanding of the geographic world. It integrates causality into design and operations, applying robust algorithms and visualization tools for scenario analysis. Unlike traditional GIS, our approach prioritizes an event-based model, emphasizing change as the core concept. This model moves beyond object-oriented models' limitations by considering events as primary entities. The proposed system adopts an event-oriented approach within a Spatio-Temporal Information System, with objects in space and time viewed as event components linked through processes. We introduce an innovative event-based ontology model that enriches GIS by focusing on modeling changes and their interconnections. Lastly, we suggest an IT implementation of this ontology to enhance GIS capabilities further.

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1 Introduction

GIS has advanced significantly over the past 50 years, transforming geographic research and applications and demonstrating its value to various fields such as urban planning, environmental management, disaster response, through its continuous evolution [11, 12, 8, 21]. GIS has evolved from computer mapping to spatial analysis to solving geographic problems, incorporating our understanding of spatial configurations and perceptions into its approach [25, 24]. Furthermore, GIS is becoming increasingly even more important in our increasingly data-driven world. With its ability to store, manage, and analyze large amounts of geospatial data, GIS aims to provide a powerful tool for solving real-world problems in a variety of domains. This rapid explosion of Geographical data has become one of the biggest challenges facing GIS today. The integration of heterogenous data from multiple sources, making this data available, analyzing it, and using it to make informed decisions is a monstrous task to fulfill. To make this even more challenging, we need to consider in to account that many decisions need to be made real-time or near-real-time in today's increasingly more complex dynamic world. A GIS capable of handling the requirements of a dynamic complex and connected world is yet to be realized. This new GIS not only needs the development of new and innovative methods for visualizing and analyzing geographic data, but more importantly it should be able to represent real-world causal relationships and enable (near)-real-time inference based on continuous flow of data. To address the challenges facing humanity, it is necessary to perform inference of causal relationships, identify effects, and conduct

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complex dynamic simulations in human-environment systems [4, 13]. A system that can accurately depict reality's dynamic nature and delineate the relationship between causes and effects, thereby facilitating causal reasoning and inferencing, can aptly be defined as a causality-enabled GIS or, in essence, a causality-aware GIS.

In the next section first the meaning of causality is discussed and the term causal aware GIS and events as its cornerstone are briefly examined. In section 3 differences between event-based models and object-oriented models in GIS are reviewed. In section 4 the proposed event-based model is illustrated and next steps to implement the model in an IT system is listed. Finally, Chapter 5 concludes this article.

2 Causal aware (GIS) systems

Causality refers to the causal relationship between a cause and its resulting effect, where the cause plays a role in producing the effect and the effect is dependent on the cause [5]. "Causality is a relation within the realm of conceptual objects. The relation of cause and effect refers to conceptual events regardless of the relation of the latter to reality" [20]. Causality is a fundamental concept in many fields, including physics, philosophy, psychology, and economics. The earliest recorded inquiry into the relationship between cause and effect can be traced back to Aristotle's Physics, which was the first known study of this nature within the realm of science [9]. Philosophy tries "to determine what causal relationships in general are, what it is for one thing to cause another, or what it is for nature to obey causal laws. As I understand it, this is an ontological question, a question about how the world goes on" [23]. Bunge [5] divides the causal problem into two subsets: a) "The ontological problem of causality, i.e. what is causation: what are the characteristics of the causal link; to what extent are such links real; are there causal laws; how do causation and chance intertwine (and so on)?" and b) "The methodological problem of causality, i.e. what are the causation criteria; how do we recognize a causal link and how do we test for a causal hypothesis?" This research focuses on the ontological problem of causality and is interested in causal links, processes as well as causal relations among events.

Causal awareness means a system, agent, or individual's capability to comprehend and account for cause-effect relationships in their environment. This ability enables more than mere correlation, promoting accurate predictions and decisions by considering causal links. Causal awareness aims to enhance decision-making and prediction precision by focusing on underlying mechanisms behind events rather than mere statistical patterns [29]. A causally aware system can thus make informed decisions and accurate predictions by understanding causality, providing a deeper comprehension of complex systems. Developing causally aware geographical systems is key for accurate comprehension of our world, however, systems seamlessly integrating spatiotemporal interactions and causal relationships are still lacking [16]. A causally aware GIS understands and considers cause-effect relationships in a geographic context. Such GIS not only contemplates causal relationships between various events within a geographical space but also leverages causality to analyze interplay between physical, social, environmental, and economic events.

Incorporating causality into GIS involves integrating causal models, algorithms, and data structures for storing and analyzing causal information. To further clarify, causal models refer to the representations that describe the causal mechanisms of a system. These models could be encoded as a system of equations, a directed acyclic graph, or a detailed computational model. Algorithms used in causal analysis commonly include techniques for learning the causal structure from data, methods for causal inference, and procedures for sensitivity analysis. Data structures suitable for storing and manipulating causal information can include ontologies for representing causal knowledge, database schemas for storing causal data, and file formats for interchange of causal information. These structures ensure efficient retrieval and modification of the causal data. The development of user-friendly interfaces for exploring causal relationships and outcomes is also a critical aspect of integrating causality into GIS. Such interfaces can support users in interpreting the output of causal analyses, navigating through causal structures, and interacting with causal data. This GIS may combine traditional techniques with causality, machine learning, AI, probability, and network analysis methods. A causally aware GIS is a largely unexplored area in GIScience that requires significant research investment. Understanding events, the building blocks of causality [5]. According to Bunge [5] "the causal relation is a relation among events". Events help us understand causation, the mechanisms linking cause and effect. Events, instances of processes occurring at specific times and places, involve changes in object states. Galton [10] discusses the complexity of causality, including the roles of states, processes, and events, and the challenges of understanding causality from an ontological perspective. Considering these components can enhance understanding of an event and its impact.

Events and their behavioral patterns represent a higher level of knowledge in comparison with changes caused by them. Therefore, they are more valuable for decision makers for making informed decisions. To explore the mechanism of changes, one must investigate the mechanism of events; indeed, events underlie changes [6, 33]. In another word, the Event-based modelling reinforces representation of dynamic behaviors of geographical phenomena, generation of hypothesis, investigation of scientific complex relationships, and ability to explore causal relationships among associated entities while providing an opportunity to understand underlying procedures [3]. In this research "event" as the basic units of causality is further explored and discussed in the next section. While the current paper provides a preliminary outline for a causality-aware GIS centered on events, it is important to note that is is impossible to cover the breadth and complexity of the literature on event ontology in this writing. However, to gain a more in-depth understanding of the connection between processes and events, readers are referred to the vast body of work by Antony Galton or references such as [31] and [1].

3 From object-oriented view toward event-based models in GIS

Initially, GIS modeled geographical features independent of time due to their long-lasting identities and locations [29]. However, in the late 80s and early 90s, GIS started to incorporate time, addressing geographic feature dynamics [2, 19]. This allowed for recording object history and predicting future changes. Still, the focus remained on geographical features, with time stamps tracking feature states [32]. This object change view, reflecting ontologies that have dominated western thought since Aristotle's time [30], sees the world as a collection of classified objects with specific properties, relationships, and behaviors. Hägerstrand [15] highlights the importance of time in human activities to assess the dynamic behaviour of people in space, especially the motion of individuals in space and time. Miller [26] and Yuan [34] have exhibited this fact in their work on transportation and urban analysis, and on analysis of physical phenomena, such as storms. Different researchers such as Miller [26] have promoted the work of Hägerstrand's under the principal of geo-spatial lifelines. However, Hornsby and Egenhofer [17] deal with the object change view through the concept of identity-based change. There are several downsides when modelling changes with the object change view [19, 32]: first, expensive computations and calculations are needed to detect and identify changes between snapshots. Second, developing or imposing rules for internal reasoning is challenging, since there is no understanding of the restrictions upon the temporal structure. Third, no matter what the size of changes is, a full snapshot is produced at each time sequence leading to storing huge amount of redundant information. Fourth, when models concentrate on objects' changes rather than a snapshot, it becomes challenging to identify "when and what change becomes so substantial that an object is no longer the same object". Due to such restrictions in the object-oriented model, many researchers have suggested event-based models as an alternative solution [7, 28, 33, 32, 29].

In event-based models, change is the main concept that is modelled and change units are the primary items for analysis and evaluation. Claramunt and Thériault [7] define events as things which occur. Particularly they explain that processes cause changes in the state of objects, these changes reveal the outcome of the process and create events. The event perspective sees objects in space and time merely as information elements of the events, which are connected to other event elements through internal or external processes [29]. Peuquet [27] defines an event as indicator of changes in a place or an object. Peuquet and Duan [28] refer to an event as a way to represent spatiotemporal manifestation of processes. Worboys [32] and Worboys and Hornsby [33] define an event as a happening that should be differentiated from a thing or continuant. They suggest that events are necessary to record the mechanism of change. Events are perhaps the most extensive information container for dynamic geo-historical phenomena and geographical reality [29]. To explain any event well enough, we should take into account its objective and results, its individual participants, its place in space and time, and its relationships to various other events. Representing enough large number of events along these dimensions may enable us to analyze and discover underlying social historical processes of the globe [14]. Although early calls to maintain and preserve records of events and processes to understand dynamic behaviours of the reality go back to late 80s [6], its realization in GI Systems is far from being called done [29].

Most early GIS data models can be considered as expansions of cartographic models, and existing methods to organise and store data generally use data layers and spatial blocks [18]. This radically limits expressing reach relationships between geographic elements at different scales, the mechanisms of interaction among elements, and their evolutionary processes with different semantic meanings and multiple attributes [22]. Hence, the need to move the concept of "representing geographical reality" beyond the principle of mapping objects which have distinct spatial, temporal and attributive identities as usual in object-oriented systems [29]. Although GIS is an information system, its core idea is to explore the geographical reality and real-world complexities, its patterns, processes, and reach interactions among different geographical phenomena, to enable us to understand the world better. Using a generic event-oriented perspective to implicitly represent causal relationships among different components of a Spatio-Temporal Information System makes realization of this goal possible. Thus, the core of GIS should follow the mission to explore the laws of nature and reveal its essence to humanity, which cannot be achieved by considering events and process as second-class elements in today's GIS systems. Leveraging event-oriented representations of reality, enables GIS to serve as a true knowledge representor of real-world complexities and move toward a causal-aware system.

4 Event-based models

Spatiotemporal ontologies have been extensively researched, but there is a notable gap in explicitly considering events as entities within GIS. Previous studies focused on modeling events and their relationships, often treating the temporal dimension as an attribute of spatial objects or as a part of new entities called "spatiotemporal objects." To bridge this gap, this study introduces a conceptual model to mirror and manage real-world dynamism. In this novel system, events unfold, processes occur, and states change. The study goes beyond conventional mapping practices that view objects as static geographic entities. Instead, it centers on modeling change as the core concept, with the analysis and evaluation primarily based on change units. This approach prioritizes the temporal dimension, recognizing the crucial role of recording event sequences over time. To handle the complex relationships between spatial and temporal dimensions, new methods are necessary. Events serve as identity containers for objects, states, and processes, forming the fundamental components for mapping dynamic phenomena. By treating events as first-class objects in GIS, this proposed event-oriented perspective enables the modeling of causality and complex relationships in our dynamic world. The mapping perspective shifts towards viewing the world as a network of interconnected relationships, unlocking richer language and understanding interactions among objects, events, and underlying processes.

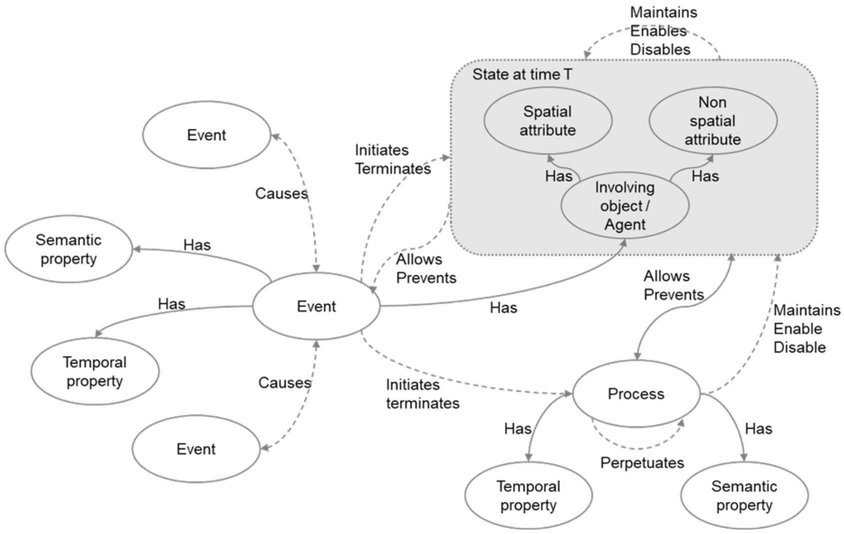

Figure 1 Schematic concept (modified version of model proposed by Polous [29]).

Figure 1 illustrates the schematic concept of the event-centric perspective. This new perspective integrates two aforementioned mapping principles; an event centric approaches that look at the phenomena holistically while in its turn inherited the object-oriented perspective for mapping the object in reductionist way. In this new integrated model, objects belong to states while processes are running on them and making changes in their states (spatial and none-spatial) through the power of events as causal forces. In fact, the states and processes together create a new concept so called 'dynamic snapshot' at each moment. The snapshots contain both processes and objects, therefore they are no longer static but have an inherent dynamism which provides a solid foundation for understanding events which are happening over time. The events can initiate or terminate a state through initiating or terminating an external or internal process. Indeed, by looking at the dynamic snapshots we can see different objects, in various states which are undergoing particular processes. The snapshots are constantly renewed as time passes; the snapshots alter from one moment to the next, because the present elements in the snapshot are changing. Here, the events are considered as fixed historical records so as time passes, event are occurring, and getting gradually added, numbered and stored in the event database. This new perspective offers a Spatio-temporal Information System a standard way to mathematically model the changing world while developing a firm basis for the logical modelling of dynamical systems.

In the pursuit of incorporating an event-based ontology model within an IT system, the Author is implementing a meticulous seven-step strategy, utilizing key tools like the Web Ontology Language (OWL) and the Resource Description Framework (RDF). The first step revolves around defining the ontology using an OWL ontology tool such as Protégé, including elements such as events, processes, states, and involved objects. OWL allows the creation of detailed and consistent models by providing greater machine interpretability than XML, RDF, and RDFS. Its reasoning capabilities enable the automation of data consistency verification and allow querying beyond instance retrieval. Subsequently, instance data tailored for particular use cases will be populated within the ontology. As a third step, we will integrate the defined ontology with other existing GIS models. The fourth stage involves data storage through RDF, facilitated by an RDF database. RDF is a standard model for data interchange, offering broad interoperability, which enables the integration of data from various sources. Its graph-based data model provides flexibility in representing knowledge, allowing users to structure and link data in any way. The data will then be queried through the SPARQL query language in the fifth stage, unveiling hidden connections and relationships within the data. SPARQL, with its capabilities to express queries across diverse data sources, supports complex reasoning tasks and extraction of valuable insights from the semantic data.

These first five steps are enough to conduct needed research for any specific use-case, however, to expand the reach of the system, the Authors aim to make the IT System available to others through APIs and User interfaces. The sixth step focuses on the development of APIs or web services, integrating the knowledge management system with additional GIS applications and allowing for external querying and support in decision-making processes. .To conclude, a user-friendly interface and visualization tools will be constructed to foster user interaction with the ontology, thus improving the overall usability of the system. By applying this model to an IT system underpinned by Semantic Web technologies, we anticipate constructing a robust knowledge management system. This system will empower users to navigate intricate relationships, inform decision-making processes, and provide valuable insights for a myriad of stakeholders. Through the leverage of Web Semantic languages such as OWL and RDF, this model offers extensive manipulation and reasoning capabilities, enabling users to create, manage, exchange, and reason with knowledge about resources. This expands the range of capabilities and empowers users to generate and explore complex relationships and hypotheses. The findings from this endeavor will be published in due course.

5 Conclusion

GIS strives to offer a complete and accurate understanding of geographic data, but the explosion of data complexity and the dynamic nature of our world poses challenges. Thus, the next logical step is to develop a causally aware GIS - a system that understands and integrates causal relationships and supports real-time decision making. A causally aware GIS enhances data analysis by considering causal relationships between various factors in a geographical context. To realize this system, we need to infuse causality into its design, operations, and analysis processes. This includes integrating causal models, algorithms, and structures that support the manipulation and analysis of causal information. Crucially, the system should be capable of computing various scenarios' effects and outcomes and clearly representing causal information. This needs to be complemented with user-friendly visualization tools for exploring causal relationships and their implications. Historically, GIS models had limitations in expressing the interaction and evolution between geographic elements. An event-based model, which sees change as the primary concept being modeled, can better represent dynamic geo-historical phenomena. As a next step, this paper proposes the development of a causally aware GIS system that comprehensively represents reality and understands causal relationships. This requires innovative methods for visualizing and analyzing geographic data, coupled with a deep grasp of causality. Implementing the proposed event-based ontology model within an IT system is a pivotal step in this direction, involving seven systematic steps from constructing the ontology to developing user-friendly interfaces and visualization tools.

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