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Using Geographic Ontologies and Geo-Characterization to Represent Geographic Scenarios

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Abstract: Traditional Geographic Information Systems (GIS) represent the environment under reductionist thinking, which disaggregates a geographic environment into independent geographic themes. The reductionist approach makes the spatiotemporal characteristics of geo-features explicit, but neglects the holistic nature of the environment, such as the hierarchical structure and interactions among environmental elements. To fill this gap, we integrate the concept geographic scenario with the fundamental principles of General System Theory to realize the environmental complexity in GIS. With the integration, a geographic scenario constitutes a hierarchy of spatiotemporal frameworks for organizing environmental elements and subserving the exploration of their relationships. Furthermore, we propose geo-characterization with ontological commitments to both static and dynamic properties of a geographic scenario and prescribe spatial, temporal, semantic, interactive, and causal relationships among environmental elements. We have tested the utility of the proposed representation in OWL and the associated reasoning process in Semantic Web Rule Language (SWRL) rules in a case study in Nanjing, China. The case study represents Nanjing and the Nanjing presidential palace to demonstrate the connections among environmental elements in different scenarios and the support for information queries, evolution process simulation, and semantic inferences. The proposed representation encodes geographic knowledge of the environment, makes the interactions among environmental elements explicit, supports geographic process simulation, opens opportunities for deep knowledge mining, and grounds a foundation for GeoAI to discover geographic complexity and dynamics beyond the support of conventional theme-centric inquiries in GIS.

Keywords: geographic environment; scenario; general system theory; evolution; interactive mechanisms; ontology

1. Introduction

Geographic Information Science (GIScience) contributes knowledge and computing frameworks to understand dynamic processes and develop solutions to geographic problems [1–5]. Major progressions throughout the past three decades have been shifting the foci of GIScience research from static distribution patterns to dynamic phenomena, space-time interactions, and evolution processes [6–10].

Such shifts demand re-examining the nature of geographic environments with considerations of environmental processes and geographic cognition to construct a holistic representation framework [11].

Geographic cognition is a psychological process with which people perceive, encode, and understand the environment [12–14], and it is likely discrepant due to different educational backgrounds, living environments, or personal preferences [15–17]. Conventional approaches to GIS data modeling disaggregate the geographic environment into various independent themes and abstract them to different layers to understand the environment in a structured way and efficiently store geographic data. These data models reflect the cognition of reality and emphasize the spatiotemporal distribution of each theme [18–20]. Extensive GIS data models represent these themes in layers of vector or raster constructs. These data models mimic the map model with different emphases, which can be classified into two categories. First, object-oriented models represent the spatiotemporal relationships among geographic objects [20–23]. Among these models, time, space, and attribute are three basic components that are used to characterize each geo-object [24]. Object-oriented models support direct mapping to represent moving objects over multiple granularities [25–27]. The second category of GIS models attempts to capture events and changes, and it arouses enormous interest in GIS to engage geographic processes and causality in discussions [28–32]. Event-based models provide opportunities to elicit geographic dynamics and discover new knowledge beyond what is attainable from layer-confined objects.

Nevertheless, both categories of traditional GIS data models subscribe to the reductionist's thinking in representing geography and neglecting the holistic nature of the environment. These models use linear superposition of representative elements [33] and they are incapable of representing the dynamic, complex three-dimensional (3D) geographic environment [34,35]. As such, GIS data models privilege space over time, in that spatial objects are defined by geometries with spatial coordinates (or cells) and time is regarded as an attribute to spatial object [36]. Consequently, changes to geometries invoke changes to object identities, limiting GIS abilities to compute geographic complexity and dynamics [30,31]. Moreover, while previous models can identify changes that resulted from object interactions, these models give no attention to the actual interactive mechanisms that explain the formation of the environment and various geo-phenomena [37]. They can represent states or changes to individual objects or cells, but also neglect connections among objects and their hierarchical structures. Hierarchical connections of components across multiple levels of geographic processes remain challenging, even though network models make explicit the topological relationships among lines and nodes.

It is significant to re-examine the connotation of geographic environment and propose a new conceptual framework considering the relationships between different environmental objects to overcome these challenges. Thus, Lv proposed the concept Geographic Scenario [17,37,38] as an environmental synthesis of elements and events. The scenario-based representation encompasses spatial, temporal, semantic, attribute, interactions, and processes. Moreover, this framework makes explicit connections among geographic objects, events, and processes and, hence, opportunities for mining knowledge about geographic dynamics, and it serves as a blueprint for holographic information systems in the future. In our study, we first recognize the essence, as well as the classification principles, of geographic scenarios and then integrate ideas from General System Theory (see Section 3.2 for details). Moreover, we summarize several typical descriptions used in geographic studies to extract the components of a scenario. The extracted components have distinctive properties and they interact with each other to form the wholeness of a geographic system. We introduce the concept of geo-characterization to express the characteristics of geographic scenarios and components. Geo-characterization depicts all the properties of a scenario and it consists of three elements as static information, process information, and relational information (see Section 4 for details). As such, a unified characterization of geographic information captures complex and dynamic properties of a geographic system. Moreover, simulations of geographic complexity and dynamics in the geo-characterization may reveal causal relationships beyond what is possible from the current GIS layers that only represent states of geography.

We expand upon the development of geographic scenarios to build the proposed geo-characterization with geographic ontology, including demonstrations of support for geographic complexity and dynamics. We analyze the characteristics and classification principles of geographic scenarios (Section 2). We apply ideas from General System Theory and explain the components of geographic scenarios that aim to answer the questions about who, where, when, what, and how (Section 3), and the proposed geo-characterization to describe the properties of geographic scenarios and components (Section 4). We develop a case study in Nanjing, China to demonstrate the ontological inferences of causality and evolution (Section 5). Finally, we present our conclusions and discuss future works.

2. Understanding the Nature of Geographic Scenario

2.1. Characteristics of Geographic Scenario

A geographic scenario is an instance of an integrated human and natural environment with specific structures and functions [38]. It is a multi-hierarchical representation method, which is proposed as the next generation of map. The geographic scenario focuses more on the holism of the environment and aims to illustrate interactive mechanisms as well as the environmental processes in geographic representation when compared with the map, which is sufficient in representing spatial, temporal, and semantic information.

Figure 1 gives an example of the structure of geographic scenarios. Moreover, eight basic characteristics of geographic scenarios are summarized with references to relevant researches [17,39,40]: (1) Multi-hierarchy: A geographic scenario consists of multiple sub-scenarios, and each sub-scenario inherits basic attributes from its parent scenario. (2) Fuzzy boundary: Fuzzy, as a common tendency in geospatial phenomena, might exist in geographic scenarios. Such problems come from two basic sources. First, the boundary itself is ambiguous and lines or transition zones can approximate it, e.g., the boundary of a forest. Second, limitations from the chosen observation technique can lead to fuzziness, i.e., from a 10-meter satellite image, we cannot measure the length of a coastline in the sub-meter accuracy. (3) Diversity of relationships: A geographic scenario constitutes not only spatiotemporal and attribute relationships, but also semantic, causal, and functional relationships (physical, chemical, biological, and social). For instance, damages to the building resulted from physical interactions with a hailstorm; the corrosion of a statue is a chemical response to an acid rain. (4) Complex structure: Geographic scenarios may have complex horizontal and vertical structures. These structures are often expressed by different relationships between the inner elements and are determined by their spatiotemporal properties or interactions. (5) Flexible scales: The spatial range of the geographic scenario varies, which can be macro scale (e.g., global scenario), meso scale (e.g., city scenario), and micro scale (e.g., campus scenario). Such flexible scales may lead to transitions between geographic scenarios and geographic features. For instance, a shopping mall affords an indoor scenario for the customers, but it serves as a feature in urban planning. (6) Functional diversity: a geographic scenario can have various functions. For instance, the Great Lakes in North America store and supply water and can regulate regional temperature. A parking structure is not only for parking, but it can function as a temporary shelter in time of severe weather. (7) Multiple dimensions: A scenario is an integral of space and time that regards the temporal dimension as important as the spatial dimension. Based on application needs, the space might be two- or three-dimensional. Hence, a geographic scenario might be of three or four dimensions. (8) Openness: Geographic systems are naturally open and in constant interaction with the surroundings. Hence, geographic scenarios are open. However, domain applications may circumscribe a confined area and assume a closed system. For example, research on the domestic travels during spring festival can consider China as a closed scenario.

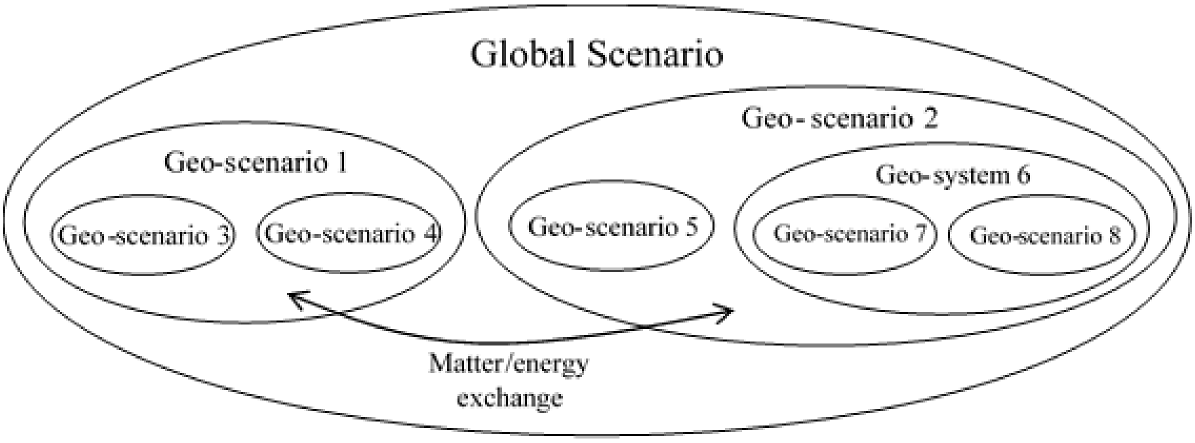

Figure 1. Structure of the geographic scenario. In this figure, geographic scenario is replaced by Geo-scenario for short. Global Scenario represents the entire earth, which is the largest unit on Earth. The overlapping between two scenarios represents their hierarchical structure, e.g., Geo-scenario 5 is the child scenario of Geo-scenario 2. Matter/energy exchange may occur between any two geographic scenarios, e.g., Geo-scenario 1 and Geo-scenario 2.

2.2. Classification Principles of Geographic Scenario

(1) We define four principles for classifying geographic scenarios that are based on physical geography regionalization, land use classification, and landscape ecology [39–41]. Principle of comprehensiveness. During the classification process, the similarities and differences of both scenarios and inner elements should be evaluated to summarize their general characters. These characters are the determining factors for further classification.

(2) Principle of dominant factors. Based on the comprehensive principle, dominant factors that lead to distinctive variations between geographic scenarios at the same level should be figured out. These factors are important to determine the boundary of each scenario and they should be consistent during the classification process at each level.

(3) Principle of relative stability. A geographic scenario should be relatively stable to exist, in which different components interact together to form a cohesive whole. Since most geographic scenarios are changing dynamically, relatively stable does not mean perfectly still over their entire life cycles, but it depends on the length of time. It should be noted that the length of time may vary considerably among different scenarios, and needs to be adequate for internal self-regulation. For instance, a city can exist hundred years, while the earth has existed for trillion years. However, if the state of a classified scenario is changing at arbitrary time scale that cannot withstand any disturbance, such a classification is not representative.

(4) Principle of human-orientation. A geographic scenario is a coupling system with natural environment and human beings. The classification of the geographic scenario should put more emphases on the behaviors of people and impacts on the environment, since human-oriented GIS has become popular in recent years.

The above principles reflect the definitional properties of geographic scenarios as the foundation for subsequent classifications in different fields.

3. Elements of Geographic Scenario and Their Connotations

3.1. Categorizing Scenario Elements

As mentioned above, elements play an important role in formulating a system. Conventional geographic information systems use features and objects to represent geographic things without substantial mechanisms for capturing the organization and dynamic relationships among features or objects. Alternatively, we considered two forms of geographical expressions with six constructs, and listed three typical expressions as the example of each construct (Figure 2): spatiotemporal element with constructs of time and location and entity-based elements with constructs of people, thing, event, and phenomenon. These forms can provide basic information in a more straightforward manner when compared with the classic expression. Some constructs may have blurring boundaries. For example, a hurricane is an event and a physical phenomenon. A storm can be conceptualized as a thing, a process, or a phenomenon. The proposed framework allows for such conceptual flexibility. However, a storm as a thing or as a phenomenon will have different geo-characterization and, therefore, they will have different properties and allow for different reasoning in the proposed framework. Details of each construct are explained below.

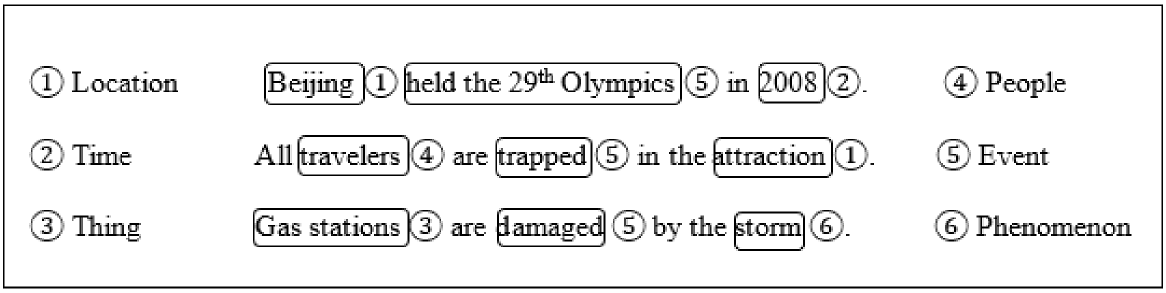

Figure 2. Sample expressions of geographic scenario.

Spatiotemporal elements are consistent with the foundation of GIS representation, which describe the spatiotemporal extents of a geographic scenario and its geographic elements. With this element, a GIS can answer questions regarding when and where with coordinates and reference systems and spatial and temporal relationships, like near, contain, before, etc.

Entity-based elements center on the entities of interest, including people, things, events, and phenomena. The rapid development of social networks and sensor technologies popularizes studies on human trajectories to reveal the underlying mobility rules. An entity-based element is consistent with the conceptual and computational needs of human trajectory analysis on individuals or groups to discern different geographic scenarios.

Things refer to independent elements with different properties in a geographic scenario. With reference to the earth sphere and classification of fundamental geographic information [42], we organize 'Thing' into eight categories (geology, topography, soil, biology, hydrology, built thing, atmosphere, other, see in Figure 3). In the eight broad categories of things, geology includes both rock types and geological structures; soil is determined by soil types; topography, hydrology, and built thing (builders include humans or animals, e.g., dams made by beavers) represent similar features as in traditional GIS, such as contour lines, rivers, buildings, etc.; biology includes animal (except for people), plant, and microorganism; atmosphere consists of particles and meteorological factors (temperature, humidity, etc.) to denote the atmospheric condition. Moreover, there are some remaining things that are categorized as 'Other', including air, sound, light, electromagnetic field, etc. These elements are massless, invisible, immaterial fields, and they may greatly affect the geographic scenario. All of these elements constitute the composition of a geographic scenario and interact with each other in environmental processes, i.e. geology affects the development of soil, and soil provides nutrition for plants.

An event is defined as a significant occurrence in the geographic scenario. An event might have a hierarchical structure of sub-events and it might progress from initiation to disappearance. Consequences of an event manifest in both spatial and temporal domains. For instance, eventual consequences can last for microseconds, days, months, years, or even longer, and change areas from local to global. Moreover, changes that are caused by an event may be instantaneous (e.g., a sandstorm influences the visibility) or hysteretic (e.g., a sewage pollutes the downstream river). Events may be natural or manmade at the top-level classification, while the latter can be further classified as political events, economic events, military events, etc.

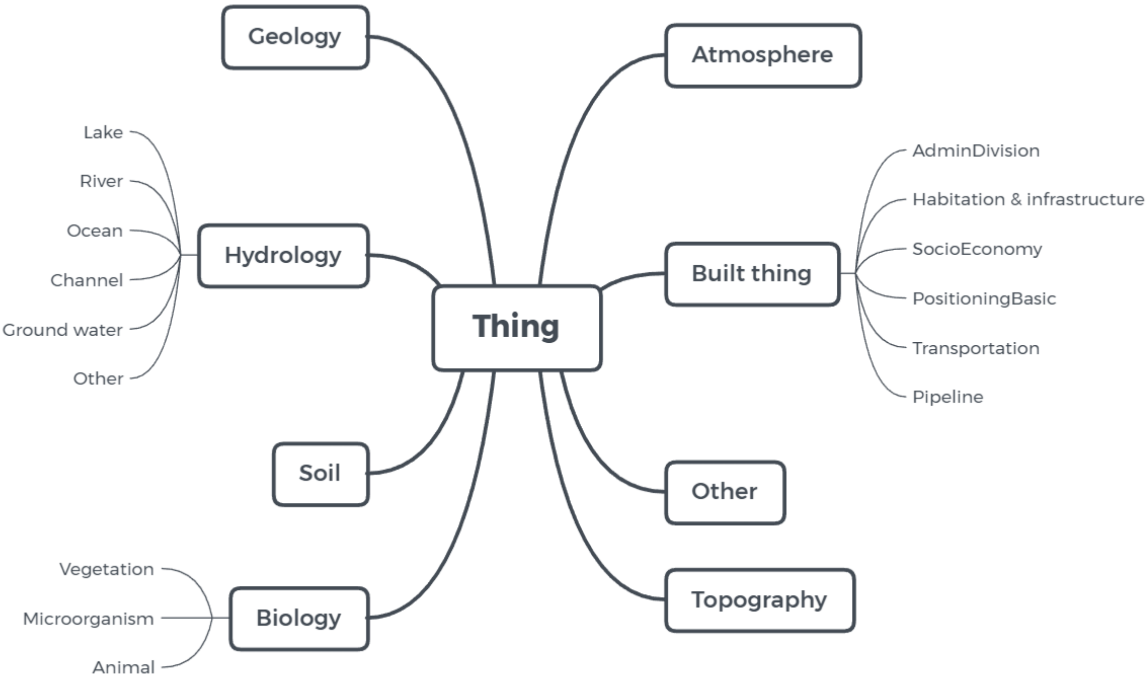

Figure 3. Classification of Thing.

Phenomena in the geographic scenario refer to the settings and conditions of existing geographic entities. All the micro, meso, and macro phenomena are included, such as meteorology phenomena (rain, lighting, etc.) and tourism phenomena (e.g., tourists travelling to coastal cities in the northern hemisphere every summer).

3.2. Relationships between Geographic Scenario and Its Inner Elements

Exploring the relationships among geographic scenario, spatiotemporal elements, and entity-based elements is essential based on the categories of geographic scenarios. To accomplish this goal, we integrate some ideas from General System Theory.

General System Theory is the basis of system sciences, which holds the view that systems are complexes composed of multiple elements. The theory opposes reductionism and emphasizes that the non-linear interactions among the systems give rise to the whole system greater than the sum of its parts [43]. Such thinking fits the idea of geographic scenarios well, thus we apply this theory in understanding the connotation and relationships in scenarios. We select several representative terms that are compatible with geographic scenarios as a mature theory with rich ideas. First, General System Theory defines elements as identifiable entities to constitute a system. These elements are interdependent with each other, where changes of an element may affect other elements and the entire system. Moreover, interaction and mutual interaction are proposed to delineate how a change in one element affects another and what reactions the affected element will respond to in the inducing element. These interactions, including both internal and external forms, organize different elements to form a cohesive conglomeration. The input and output of a system are also defined to present movements of information or matter-energy from the environment (system) into the system (environment). The inputs and outputs are important for a system to connect with its environment. Both interactions, as well as the input and output, keep the system changing and dynamically developing. Apart from these terms, the upward spiral thinking in the General System Theory holds a view that a higher level system with more elements and relationships can be introduced if a current system cannot meet the requirement to solve problems. Such thinking can be applied to explain the transition between geographic scenarios and features of a shopping mall mentioned in Section 2.1.

The integration of General System Theory assists in the conceptualization of a geographic scenario as a dynamic system and construction of the relationships of a geographic scenario to its components (Figure 4). The spatiotemporal elements are the base for describing spatiotemporal characteristics of geographic scenarios and entity-based elements in scenarios. Moreover, there are two-way changes that take place between the scenario and its component, in which the entity-based elements interact with each other to constitute the geographic scenario and could dynamically change it, while the scenario provides spatiotemporal frames, conditions, and limitations to affect the existence and development of entity-based elements. Interactions in the geographic scenario are complicated, including scenario-scenario interactions and element-element interactions, i.e., military strikes between two nations of which each nation is a geographic scenario with particular settings and under specific conditions; the scenario of "Three Gorges Dam blocks the upper-middle reaches of Yangtze River" consists of the Dam and Yangtze River as the elements.

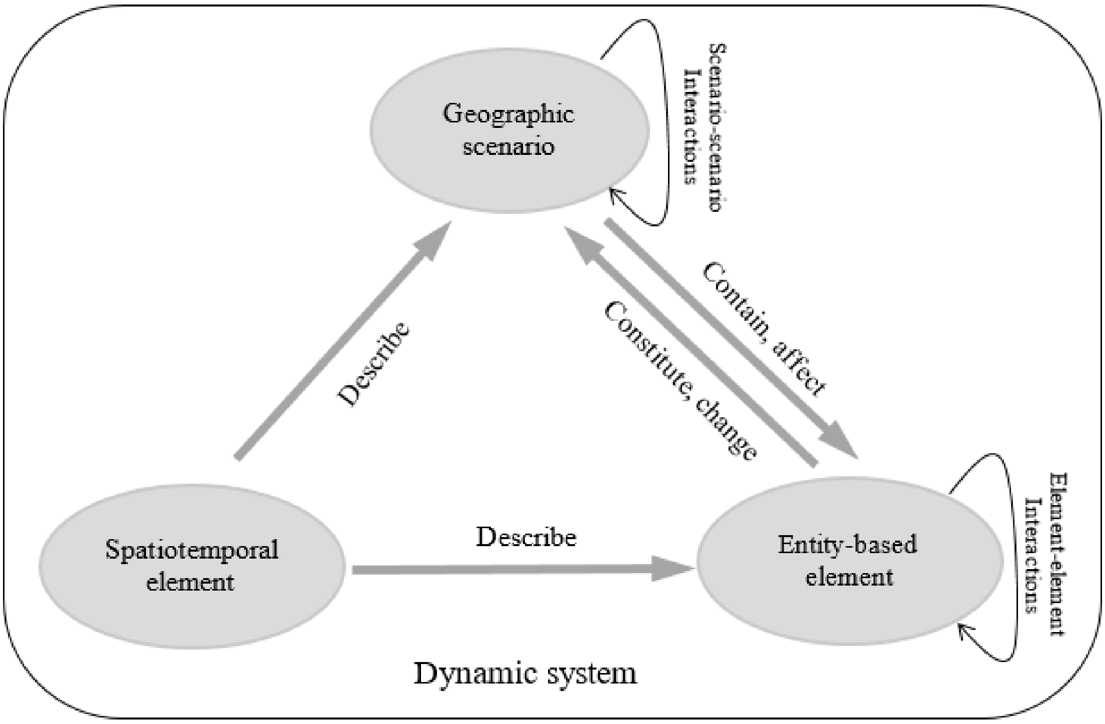

Figure 4. Relationships between a geographic scenario and its elements.

4. Construction of the Geo-Characterization

Conventional GIS models are proficient in representing spatial, temporal, and semantics information (e.g., location, spatiotemporal relationship, etc.), but they lack capabilities to express the interactive mechanisms and environmental processes in a geographic scenario. Lv proposed six factors (location, shape, attribute, geographic semantics, relationship, evolutionary process) as geographic information to describe a geographic scenario [17]. However, the concept geographic information usually indicates elements in the world but not their characteristics to overcome this deficiency. We use geo-characterization to capture all six factors of geographic scenarios in forms of static information, relational information, and process information.

(1) Static information takes each scenario or element as a separate geographic object without any consideration for the linkage with others. Static information includes spatial, temporal, semantic, and attribute information. Among them, temporal information can be expressed

by absolute time and relative time; while, spatial information focuses on the geometry and location. The three characterizations of geographic information correspond to the spatiotemporal elements of geographic scenarios. Semantic information is similar to attribute information, but the difference between them is that semantic explains 'what is this object' and attribute introduces 'what properties this object has'. Apart from spatiotemporal attributes, semantic information includes physical (humidity, conductivity, etc.), chemical (PH value, ignitability, etc.), biological (uniformity, biodegradability, etc.), and social attributes (GDP, population density, etc.). These properties are important in explaining the composition of an element and help improve predictions.

(2) Relational information captures connections between different geographic scenarios or entities. Relationships are not only spatial, temporal, and sematic relationships, but also causal and interaction relationships. All of these relationships convey rich information to answer questions, like when, where, why, and how.

We adopt the topological relationships in space in the nine-intersection model [44] and in time in Allen's interval Interval Algebra (Figure 5) [45]. Spatial relationships can include distance and orientation relationships in qualitative and quantitative ways. For example, the straight-line distance between Houston and Dallas is 225 miles; the Empire State Building is close to many hotels; and, the White House is located north to the Washington Monument.

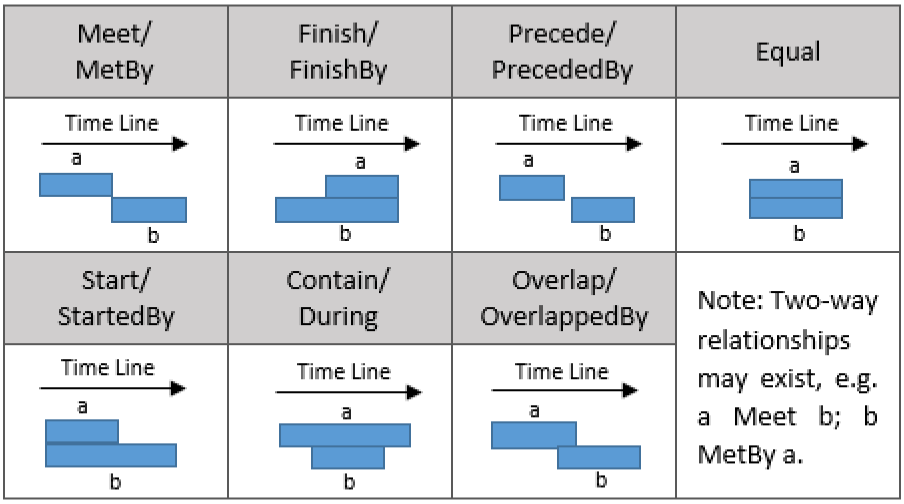

Figure 5. Temporal relationships in geographic scenarios.

Semantic relationships denote relationships among the meanings of entities. The content of semantic relationships ought to be flexible and extensible since geospatial semantics are diverse. In addition to the parent-child relationship, various attribute relationships are also included, such as correlation, ownerships, causality, etc.

Causal relationships refer to the relationships between causes and effects that prevail in geographic scenarios. Coded causal relationships reflect the current understanding of geographic scenarios and they can be applied for knowledge mining. Causalities in a geographic scenario can be complicated and be direct or indirect (Figure 6). Direct causalities have deterministic associations with driving forces that lead to predictable outcomes. For example, an explosion in the mountain causes a landslide; the Second World War led to global economic slump, collapsing population, and destruction of residential areas. An indirect causality connects seemingly unrelated elements, which suggests potential causes to an issue. Following the landslide event that is caused by an explosion, the landslide destroys the mountain road and leads to casualties and road closures. Without recorded indirect causal relationships, uncovering the source (exploration) of consequent events would be challenging. GIS databases with causal relationships can promote mining cascading events and event consequences.

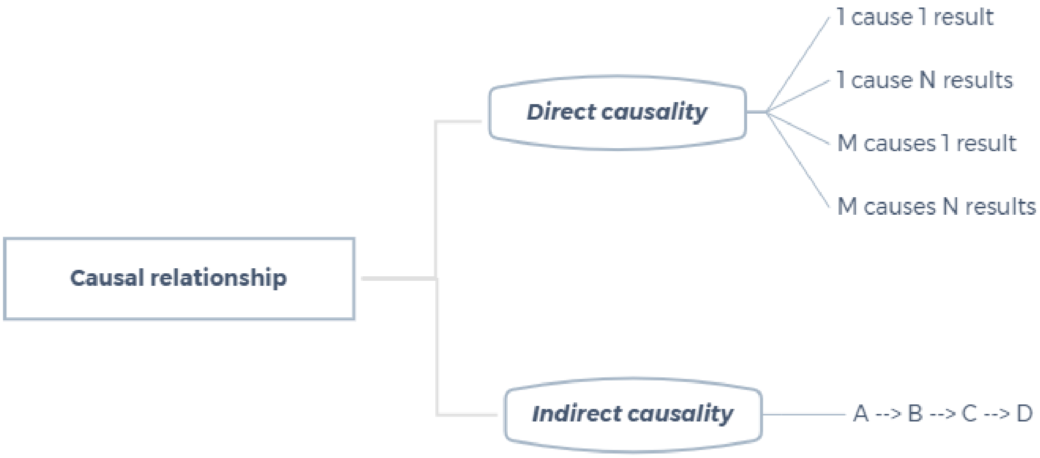

Figure 6. Causal relationships in geographic scenarios.

The relationships of interactions denote what interactions happened between two scenarios or elements. Interactions demand an integrative approach to system studies, according to General System Theory. Some interactions can occur in multiple geographic entities in a given region for a given time, while, over time, one or more interactions might alter an object, including chemical (corrosion, decomposition, etc.), physical (carry, block, etc.), biological (photosynthesis, respiration, etc.), and social interactions (attack, prevent, etc.). Interactions are ubiquitous in geographic scenarios, which can be used to explain various mechanisms, i.e., a mountain blocks the flow of wind, and the wind erodes the sand dunes on the mountain foothill.

(3) Process information: The idea of processes has been a hot topic in GIS researches without a unified definition so far. Many studies consider them as the same concepts [31,32], or expressions at different scales [46] due to the ambiguity between process and event. We consider that each element has its own life cycle and, hence, a process is the generality of a scenario or element rather than a synonymous concept of an event. Process information is presented in model-based or state-based ways. The former method uses accurate geographic models to express the evolution process, e.g., hydrological model, while the latter method describes the process in terms of stages and links each stage with their state and relational information. The components of geo-characterization are summarized in Figure 7.

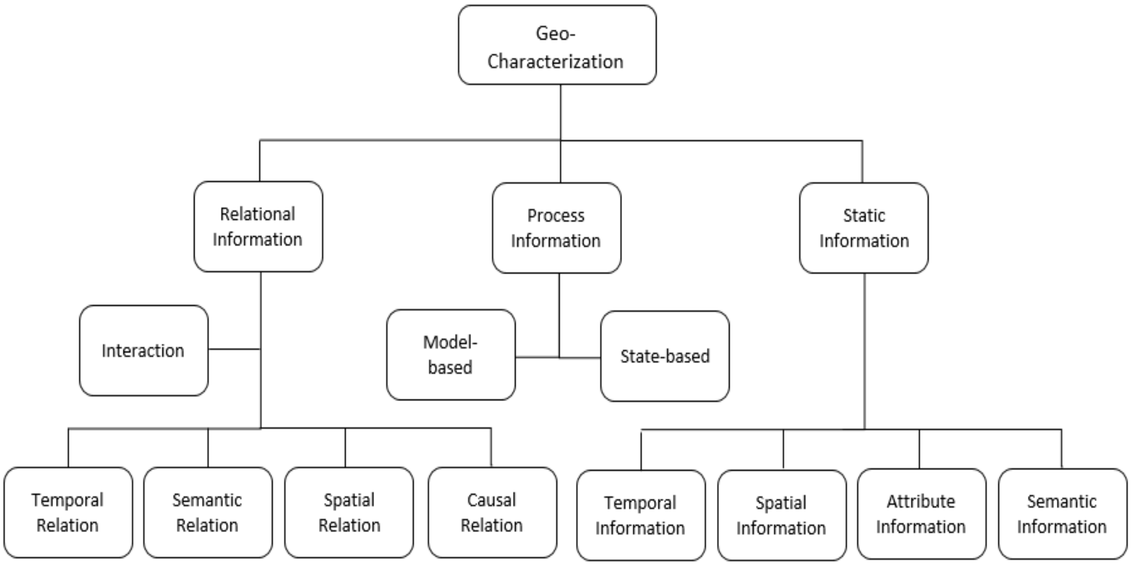

Figure 7. Components of geo-characterization.

5. Implement the Scenario-Based Representation Framework with Ontology

5.1. Construct Ontologies of the Scenario-Based Framework

We develop an ontological implementation of the scenario-based representation framework and build eight core classes with the Protégé 5.0.0 tool (https://protege.stanford.edu/), namely Geographic scenario, People, Thing, Event, Phenomenon, and Geo-characterization (Figure 8). Most of the classes (except for Geo-function and Representation) can be further classified into sub-classes, as we explained in Section 3.1, which can help to construct a more complete system. Specifically, classes for Geographic scenario, Event, and Phenomenon are divided into different classes according to human activities. For instance, Event is divided as natural event and manmade event. The Thing and Geo-characterization classes contain sub-classes according to elements in Figures 3 and 7. The two kinds of relationships are modeled as object properties based on the protégé rules since the relational information as well as the process information connects at least two geographic objects. The constructed ontological system makes the components as well as the hierarchical structure of geographic scenario explicit, which can be used to store relevant data into each class to demonstrate the utility of our proposed framework.

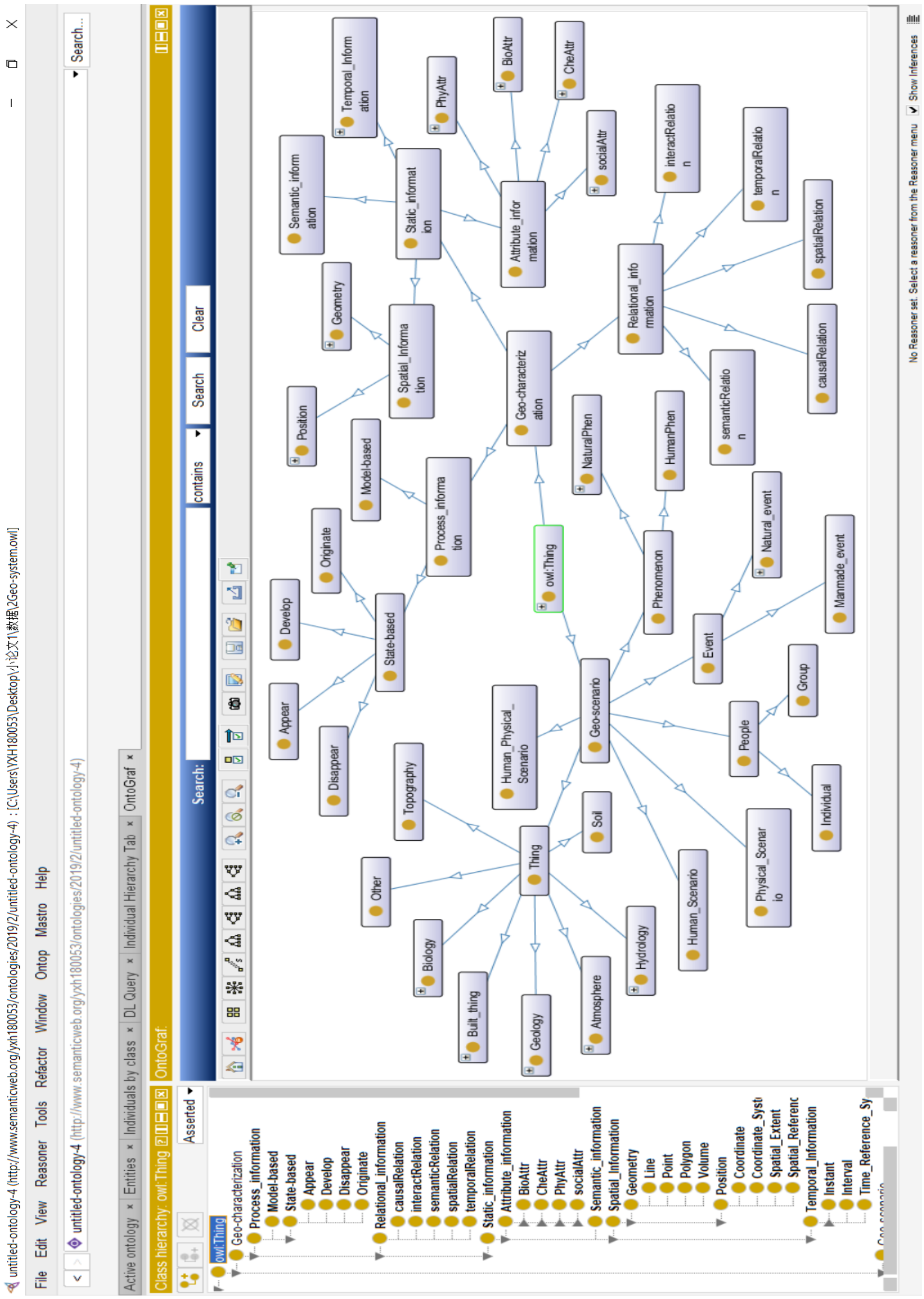

Figure 8. Screenshot for the proposed ontology.

5.2. Instance Construction

With the implemented ontology, we use Nanjing, China and Nanjing Residential Palace Attraction (NJPPA) as examples for demonstrating the utilities of geographic scenarios and geo-characterization for information expression and exploration. Nanjing is an important central city in eastern China, and the ancient capital of ten dynasties with a history existing over two-thousand years. NJPPA is a famous scenic site located in Nanjing since 1982 and it acts as the palace or government office for regional supreme rulers in modern history. The name of NJPPA has changed several times due to some important political or military events. The rich history makes NJPPA a representative place that reflects the social developments of Nanjing. Data for the case study comes from Jiangsu administrative GIS data, Nanjing tourism GIS data, Nanjing statistical bureau and the official website of NJPPA (http://www.njztf.cn/static.sh?file=lishi). Figure 9 shows the workflow of the case study.

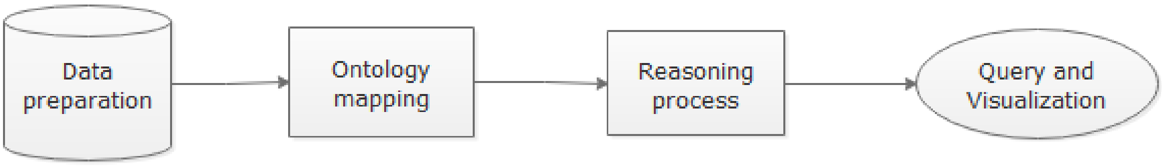

Figure 9. Flowchart of the ontological implementation of geographic scenarios.

(1) Data preparation

The geo-characterization includes various kinds of information; however, some information is beyond the scope of the current GIS database. Additional data are necessary to meet the requirements of geographic scenarios. First, we add population, Gross Domestic Product (GDP), and cities in different orientations as separate fields in the Jiangsu administrative database (Figure 10). The extended data can express the semantic, attribute, orientation relation, and hierarchical structure. For instance, the city code of Nanjing is 320,100 (semantic). It has a population of 8.43 million and the GDP of RMB 1.28 trillion in 2018 (attribute), with one parent scenario as Jiangsu and 11 parallel scenarios (at the same level of the hierarchal structure). It sits west to Zhenjiang, southwest to Yangzhou, and northwest to Changzhou (orientation relations). The Nanjing tourist map includes the attractions and their related information in each district, e.g., NJPPA is a cultural attraction in Xuanwu district, Nanjing. Table 1 summarizes the historic data of NJPPA and it shows the historic states (names and ownerships) of NJPPA at different time periods. The 'interact' column in the dataset marks the reason why NJPPA is renamed. For instance, The Ming Dynasty constructed the Han Palace as the location of NJPPA during 1368–1647. The Qing Dynasty invaded The Han Palace and renamed it as The Jiangnan Government Office (JN Gov Off). All of the extended data are stored as tables in MySQL database for ontology mapping.

NAME	CITYCODE	PROVIN	GDP	Pop	northTo	southTo	eastTo	westTo	southEastTo	southWestTo	northEastTo	northWestTo
Nanjing	320100	Jiangsu	1.28	8.43	<Null>	<Null>	<Null>	Zhenjiang	<Null>	Yangzhou	<Null>	Changzhou
Nanton	320600	Jiangsu	0.84	7.31	Suzhou	<Null>	<Null>	<Null>	Yancheng, Tai	<Null>	<Null>	<Null>
Suqian	321300	Jiangsu	0.28	4.92	<Null>	<Null>	<Null>	<Null>	Xuzhou	Lianyungang	<Null>	Huaian
Changz	320400	Jiangsu	0.71	4.72	Wuxi	Taizhou	<Null>	<Null>	Nanjing, Zhenji	<Null>	<Null>	<Null>
Xuzhou	320300	Jiangsu	0.68	8.80	<Null>	<Null>	<Null>	Lianyunga	<Null>	<Null>	<Null>	Suqian
Yangzh	321000	Jiangsu	0.55	4.53	Zhenjiang	<Null>	<Null>	<Null>	Huaian	Yancheng	Nanjing	Taizhou
Wuxi	320200	Jiangsu	1.14	6.57	<Null>	Changzho	<Null>	Suzhou	<Null>	<Null>	<Null>	<Null>
Taizhou	321200	Jiangsu	0.51	4.63	Wuxi, Ch	Yancheng	<Null>	<Null>	Yangzhou	<Null>	Zhenjiang	Nantong, Suzho
Huaian	320800	Jiangsu	0.36	4.93	<Null>	Lianyunga	<Null>	Yancheng	Suqian	<Null>	<Null>	Yangzhou
Yanche	320900	Jiangsu	0.55	7.20	Taizhou	<Null>	Huaian	<Null>	Lianyungang	<Null>	Yangzhou	Nantong
Suzhou	320500	Jiangsu	1.86	10.7	<Null>	Nantong	Wuxi	<Null>	Taizhou	<Null>	<Null>	<Null>
Lianyun	320700	Jiangsu	0.28	4.52	Huaian	<Null>	Xuzhou	<Null>	<Null>	<Null>	Suqian	Yancheng
Zhenjia	321100	Jiangsu	0.41	3.20	<Null>	Yangzhou	Nanjing	<Null>	<Null>	Taizhou	<Null>	Changzhou

Figure 10. Geo-characterization of Jiangsu province.

Table 1. Historic data of Nanjing Residential Palace Attraction (NJPPA).

ID	Name	Period	Ownership	Interact
1	Han Palace	1368–1647	Ming Dynasty	Construct
2	JN Gov Off	1647–1665	Qing Dynasty	Invade
3	LJ Gov Off	1665–1853	Qing Dynasty	PolAdjust
4	TW Palace	1853–1864	Taiping Dynasty	Rebel
5	Palace Ruins	1864–1870	Qing Dynasty	BurnDown
6	LJ Gov Palace	1870–1912	Qing Dynasty	Rebuild
7	Ntl Gov Off	1912–1937	Republic of China	Replace
8	Puppet Gov Off	1937–1946	Puppet Regime	Invade
9	Pres Palace	1946–1949	Republic of China	Reclaim
10	JS Gov Off	1949–1982	P.R.China	Replace
11	NJPPA	1982–2019	P.R.China	Renovate

(2) Ontology mapping

We start mapping the data to our ontologies once all the necessary data are in place. The relational database stores entities in two-dimensional tables, while using rows for each instance, and describes attributes in the field. Therefore, tables, rows, and fields can be converted into classes, instances, and geo-characterization in our ontologies, respectively. In particular, relationships between tables are mapped to semantic relationships in the ontology, such as parent-child relationships and containment (inverse of part-of relation), and the name of each instance is defined by the primary key of a tuple [47,48]. Based on this characteristic, we manually imported instances to the ontology. Among these classes, cities like Nanjing and Yangzhou, and Districts, like Xuanwu, are mapped to instances of geographic scenarios. NJPPA as well as its historic states are instances of infrastructure (a subclass of Thing) with attributes.

(3) Reasoning process

The multi-hierarchical scenario gathers various elements as a whole in a complex network, unlike conventional approaches in which different elements are presented in separated layers. Therefore, any element in this hierarchy is directly or indirectly related with other elements, which indicates that changes of an element could affect a seemingly unrelated element. Such a hierarchical structure provides the possibility for further inference. Thus, we use SWRL rules to reason the geo-characterization and explore hidden knowledge. SWRL rules are made by antecedent and consequent, with a deductive logic 'antecedent -> consequent'. An antecedent explains the preconditions, and a consequent shows the inferenced result. An atom is the basic component in SWRL syntax. Two common atoms ($C(x)$, $P(x, y)$) are used in the reasoning process. $C(x)$ means that x is an instance of class C, and $P(x, y)$ means that x is related with y through an object property P.

In this case, we assume that the ruling party of Nanjing is changed if the name and owner of NJPPA are changed, since NJPPA is an element in Nanjing with special historical status. Based on the assumption, we build SWRL rules to account for several semantic relationships, like contain, hasOwner, and preDominateBy (previous dominated by a dynasty) (Table 2). These rules are then stored in Protégé tool, and Jena API is called to execute reasoning and produce the results. After this process, different historic parties are associated with Nanjing. The owl file has been published online, and it can be downloaded at https://github.com/WonderfulDay123/Geo-scenario-ontology.

Table 2. Rule sentences for implicit relationships of NJPPA.

Rule ID	Rule Sentence	Comment
Rule 1	*Infrastructure (?x) ˆ District (?y) ˆ City (?z) ˆ contain (?y, ?x) ˆ contain (?z, ?y) -> contain (?z, ?x)*	*Delineate the cascading semantic relationship*
Rule 2	*contain (?z, ?x) ˆ Dynasty (?t) ˆ hasOwner (?x, ?t) -> prevDominateBy (?z, ?t)*	*Judge changes in ownership of the city*

(4) Query and visualization

Our ontologies consist of complex relationships and they are not suitable for a relational database. Therefore, we use a graph database (Neo4j) to store and visualize the results [49,50]. Neo4J provides a possible way for future massive geographic scenario data storage, query, and expression. With several simple queries by Cypher Query Language, abundant linked information can be displayed to show the superiority of our proposed representation method when compared with traditional models (Table 3). From Table 3 (a), (b), spatiotemporal relationships (hasPeriod, westTo, southTo), hierarchical structures (partOf, contain), and other semantic relationships (hasGDP, hasOwner, histState, etc.) of retrieved nodes can be clearly illustrated. Additionally, the evolution and interactions elaborate how NJPPA is developed under the renovation of P.R. China. From Table 3 (c), all interactions occurred in the history are presented in chronological order. Tons of nodes and relationships can be retrieved, including the reasoning results with the above SWRL rules, if we expand the traversal depth of NJPPA from one to three. The querying results with our proposed framework have been greatly enriched compared with traditional GIS models. It does not only focus on the spatiotemporal and semantic information, but also illustrates the complex relationships with other elements, and the interactive mechanisms to explain the evolution process. To make it more reader-friendly, we remove some nodes and visualize it in Figure 11. From this figure, information can be captured from different perspectives. For instance, it builds the linkage between different elements to represent their hierarchical structures, in which Nanjing is the parent scenario of Xuanwu, and Xuanwu is the parent scenario of NJPPA. If we focus on the internal objects of NJPPA, this attraction could be the parent scenario (which is modelled as Thing in this case) of different buildings, gardens, lakes, etc. With this hierarchy, NJPPA can be used to reason the historical ownership of Nanjing. Moreover, the evolution process of NJPPA is presented (covered by the light blue shadow), while the driven factors corresponded to each historical status. It conveys the interaction and causality that are inadequate for traditional GIS. As an example, this experiment displays the capability and potential of our proposed framework in representing comprehensive information and further solving complex geographic problems. Moreover, GeoAI has become popular in recent years, which applies artificial intelligence (AI) to geospatial problem solving. Knowledge representation holds the key to capturing concepts, relationships, and reasoning in all AI applications. Therefore, the proposed representation of knowledge about geographic systems can help to advance GeoAI.

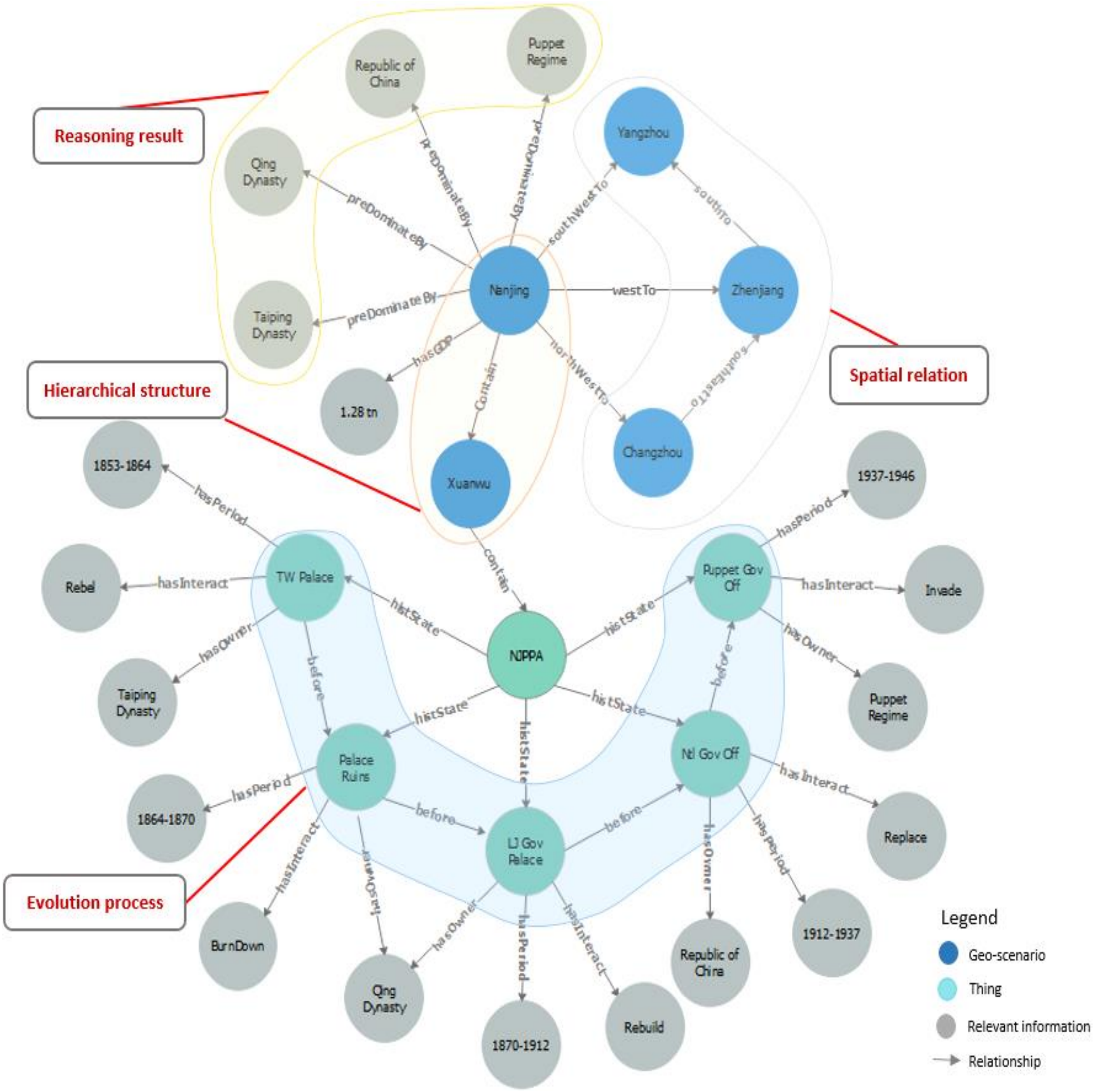

Figure 11. Part of relationships shown in Neo4j.

Table 3. Query results in Neo4j.

Query	Results

(a)
Match (n: City {name: "Wuxi"}) – [r*..1] –> (m)
Return n,r,m;
	{
	{"Wuxi",: part of, "Jiangsu"},
	{"Wuxi",: cityCode, "320200"},
	{"Wuxi",: hasGDP, "1.14tn"},
	{"Wuxi",: hasPopulation, "6.57 mn"},
	{"Wuxi",: westTo, "Suzhou"},
	{"Wuxi",: southTo, "Changzhou"},
	{"Wuxi",: contain, "Liangxi},
	{"Wuxi",: contain, "Xishan"},
	…
	}

Table 3. *Cont.*

Query	Results

(b)
Match (n: Infrastructure {name: "NJPPA"}) – [r*..1] –> (m)
Return n,r,m;
	{
	{"NJPPA",: part of, "Jiangsu"},
	{"NJPPA",: contain, "Xuanwu"},
	{"NJPPA",: hasOwner, "P.R. China"},
	{"NJPPA",: hasPeriod, "1982-2019"},
	{"NJPPA",: hasInteract, "Renovate"},
	{"NJPPA",: developIn, "P.R. China"},
	{"NJPPA",: histState, "Han Palace"},
	{"NJPPA",: histState, "JN Gov Off"},
	. . .
	}

(c)
Match (a: attraction) – [r: hasInteract] –> (b: Interact)
Return a,r,b;
	{
	{"Han Palace",: hasInteract, "Construct"},
	{"JN Gov Off",: hasInteract, "Invade"},
	{"LJ Gov Off",: hasInteract, "PolAdjust"},
	{"TW Palace",: hasInteract, "Rebel"},
	{"Palace Ruins",: hasInteract, "BurnDown"},
	{"LJ Gov Palace",: hasInteract, "Rebuild"},
	{"Pres Palace",: hasInteract, "Reclaim"},
	{"Ntl Gov Off",: hasInteract, "Replace"},
	{"Puppet Gov Off",: hasInteract, "Invade"},
	{"JS Gov Off",: hasInteract, "Replace"},
	{"NJPPA",: hasInteract, "Renovate"},
	}

6. Conclusions and Future Works

Conventional GIS representation models neglect the holistic nature of the environment and separate the environment into different themes. Such thinking makes it difficult to fully express the complex, dynamic nature of an environment. In response, we focused on the characteristics and classification principles of geographic scenarios and then applied ideas from General System Theory into GIS representation and reasoning. The theory explains the complex structures and dynamic relationships between systems and elements. We expanded the ideas of geographic scenarios with ideas from General System Theory to depict the wholeness of a system. We improved the initial scenario-based representation framework with geo-characterization and developed an ontological implementation to represent the geo-scenario and its components. This framework includes abundant geo-related information and records evolution process, interactive mechanisms, and causal relationships. We implemented the geographic scenario and geo-characterization in ontologies with a case study of NJPPA in Nanjing, China, to test its practicability. SWRL rules are built to support reasoning on historic eras in Nanjing, and final results are stored in the Neo4j database for data query and visualization.

GIS query plays an important role in attaining information regarding the dynamic geographic environment. Apart from traditional spatiotemporal and attribute queries, this case study supports querying on interactions between any two geographic elements. Based on the classification of interaction, such query can help to explain some mechanisms of the environment. Moreover, the hierarchical structure and evolution information are also retrieved. Former information is significant for linking different scenarios or elements together for further reasoning, while the latter information directly elaborates how the scenario or element evolves historically. As such, rich information, including spatiotemporal properties, complex relationships, interactive mechanisms, and evolution are obtained in this study.

This research establishes a theoretical foundation for a scenario-based unified representation and showcases an ontological implementation method that integrates geographic scenarios and geo-characterization. The structures and relationships of systems and components in the proposed framework elevate GIS data for geographic knowledge mining and GeoAI applications to explore the inner workings of geographic environments. There are several areas for further work. When developing the geographic scenario ontology, the boundaries for both scenario and its four constructs of entity-based elements are vague. In this experiment, the entities are classified into different classes based on the subjective cognition. However, some entities can be regarded as multiple classes, e.g., NJPPA can be modelled as a sub-scenario of Xuanwu district, or an infrastructure that is located in this region. Such an issue might lead to extensive work and cause ambiguity for large dataset. Thus, an automatically identification method is needed for filling this gap. Moreover, the ontological reasoning function is realized through several simple rules, which cannot support complicated inferences. It might limit the popularization of the proposed framework to a broader area. Future work should address these deficiencies to support complex geographic computation and simulation. Furthermore, there are rich sources of ontologies in geography, earth sciences, and related fields, as well as in space and time. This research only implemented a limited ontology to express the proposed representation. Nevertheless, the representation framework is founded in the general hierarchy of geographic systems and it is extensible with concepts from other ontologies. Additionally, as a simple experiment for validating the practicability of the proposed framework, the performance of Neo4J in processing large amount of data is not studied in this research. The research used Neo4J to demonstrate an implementation of the proposed representation. Future research should explore other graphic databases and assess the performance and efficiency.

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